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Emissions from Residential and Small Commercial Stoker-Coal-Fired Boilers Under Smokeless Operation

Battelle Columbus Labs, Ohio

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16. ABSTRACT The report gives results of a technical assessment of the advisability of increased use of stoker coal for residential and small commercial space heaters. The assessment was based on: (1) an experimental laboratory study (major emphasis) to evaluate emissions from a 20-hp (200 kw) boiler firing anthracite, Western subbituminous, processed lignite char (smokeless coal), and high and low volatile bituminous coals (pollutants of major interest were smoke, particulate, and POM); (2) a survey to identify manufacturers and designs of currently marketed stokers; and (3) a survey to identify processes for the manufacture of smokeless coals and to evaluate the suitability of these fuels for stoker firing. The experimental investigation indicated that smokeless operation of a small stoker could be achieved for the coals evaluated (coals generating the highest smoke levels generated the highest particulate and POM levels). Coals with the highest volatile matter and the highest free swelling index had the highest levels of these emissions. It also indicated that a potential exists to reduce emissions both by minor modifications in the stoker design and operation, and by use of processed or treated coals. Even these emission levels would be considerably higher than those from equivalent oil- and gas-fired systems.

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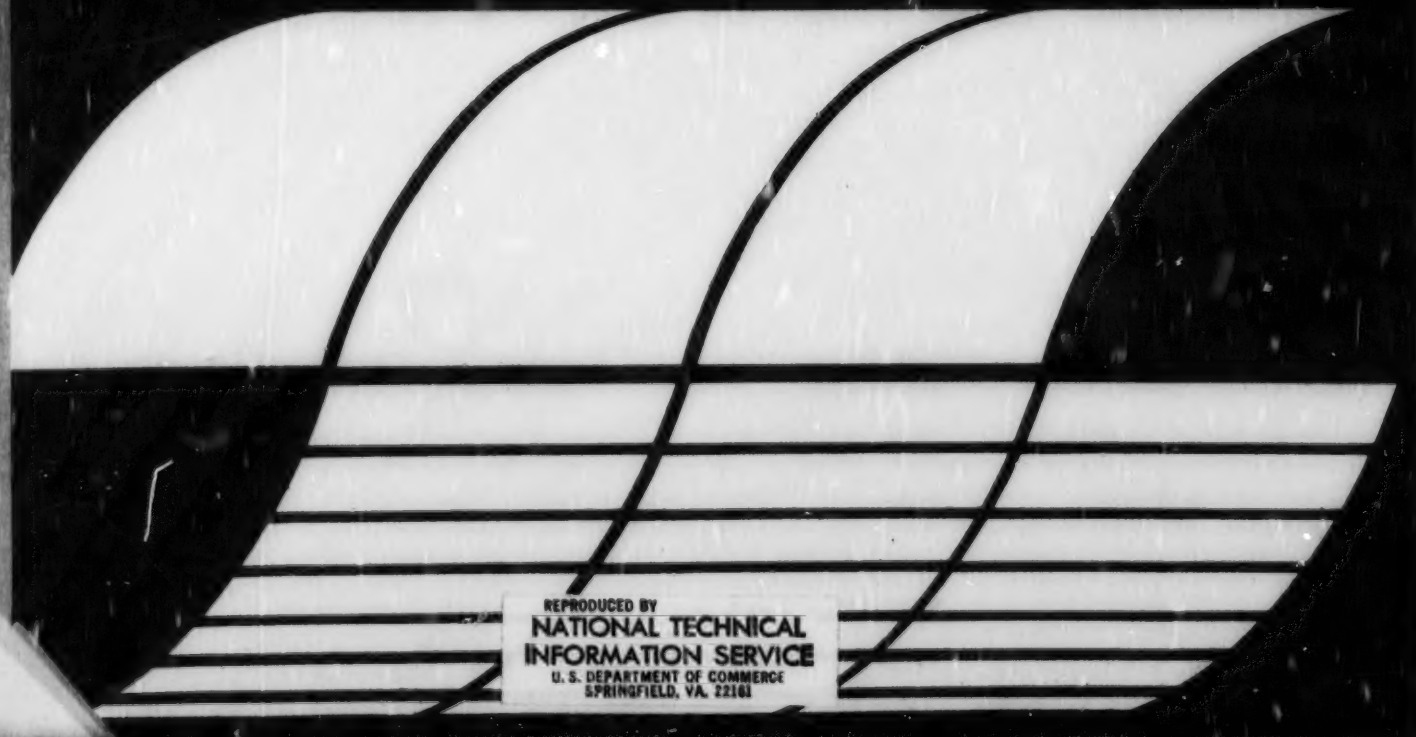

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EMISSIONS FROM RESIDENTIAL AND SMALL COMMERCIAL STOKER-COAL-FIRED BOILERS UNDER SMOKELESS OPERATION

by

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ABSTRACT

The reported research assessed the advisability of increased utilization of stoker coal for residential and small commercial space heating applications. The assessment was based on (1) an experimental laboratory study (major emphasis) to evaluate the emissions from a 20-hp (200 kW) boiler firing anthracite, Western subbituminous, processed lignite char ("smokeless coal") and high- and low-volatile bituminous coals. Pollutants of major interest were smoke, particulate, and POM; (2) a survey to identify the manufacturers and designs of stokers currently marketed, and (3) a survey to identify processes for manufacturing smokeless coals and to evaluate their suitability for stoker firing.

The results of the experimental study indicate that smokeless operation of a small stoker could be achieved for the coals evaluated. The coals generating the highest smoke levels also generated the highest particulate and POM levels. Coals with the highest volatile matter and the highest free swelling index had the highest levels of these emissions. The experiments indicate a potential for reducing emissions by minor modifications in the design and operation of the stoker and by utilizing processed or treated coals. Even these reduced emission levels would be considerably higher than those from equivalent oil- and gas-fired system.

The results of the stoker and smokeless coal surveys suggest that there is insufficient demand for small stokers to justify the needed R&D to refine stoker designs and commercialize smokeless coal processes.

Current economic and environmental factors associated with stoker firing are unfavorable for increased coal usage in residential and small commercial applications. Although our supplies of fuel oil and natural gas are dwindling, there appears to be no immediate or near term shortage for most small users. Where shortages exist, alternative methods of space heating (such as electric space heating coupled with extensive insulation) will be selected rather than stoker firing.

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SECTION 1

INTRODUCTION

Coal was still a major fuel fired in residential and small commercial heating systems as late as the 1950's. Coal usage then rapidly declined as the market areas of the less expensive, more conveniently utilized, and more environmentally acceptable fuels (gas and oil) expanded. Even in certain geographical locations where coal was cheaper than oil or gas, the high maintenance costs and labor associated with firing coal, coupled with an increased desire for a clean environment, virtually eliminated the use of coal for residential and small commercial space heating applications by the 1960's.

The emissions from residential and small commercial stokers were never extensively characterized (by today's standards) as the sophisticated instrumentation currently used was not available. However, visible smoke was easily measured and stokers were notorious for their cyclic smoke emissions. Attempts to alleviate this problem included refinement of stoker designs and development of manufacturing processes to convert high volatile coals to a "smokeless" coal. Before these designs and processes received widespread application (and further development), the stoker market disappeared. As a consequence, after only a relatively short period of research and development, advancement of the technology of stoker firing was halted.

Today, the uncertainty in both the short- and long-term availability of oil and gas has renewed an interest in burning coal to meet our nation's energy needs. To assist EPA in making a technical assessment of the environmental impact of burning coal, specifically in residential and small commercial applications, Battelle-Columbus conducted a program to evaluate the emissions from residential and small commercial coal-fired stokers. (Small commercial was defined as equipment with less than one million Btu/hr input.)

SECTION 2

OVERALL PROGRAM OBJECTIVES AND SCOPE

The overall objectives of this program were (1) to evaluate emissions from residential and small commercial stoker-fired boilers under typical boiler operation, including smokeless operation, and (2) to assess the advisability of increased utilization of coal for these applications, including consideration of operating efficiency, fuel type and availability, economics, emissions, and public acceptance. This program consisted of:

1. A survey to identify the manufacturers and designs of stokers currently being marketed

2. A survey to identify processes for the manufacturing of smokeless coals and to evaluate the suitability of these fuels for stoker firing

3. An experimental laboratory study to measure emissions while firing a stoker-fired boiler system with five candidate fuels. For this study, a 20-hp (200 kW) stoker was fired with anthracite, Western subbituminous, processed lignite char ("smokeless coal"), and high- and low- volatile bitumnious coals. Pollutants of interest included NO, SO_2, CO, smoke, particulate, and polycyclic compounds.

The major emphasis of the body of this report is focused on the experimental laboratory program; the survey of stoker manufacturers and the survey of smokeless coal processes are discussed in Appendices A and B, respectively. Pertinent information from these surveys has been incorporated in the Summary and the assessment of the potential utilization of coal for small commercial stoker applications.

SECTION 3

SUMMARY OF RESULTS

The results of the experimental research investigation, the stoker manufacturer survey, and the "smokeless" coal survey can be summarized as follows.

Experimental Research Investigation

The results of the experimental research investigation are as follows:

- Smokeless operation of a small stoker was achieved for the coals evaluated.
- In general, coals that generated the higher smoke levels also generated the higher particulate and POM emission levels.
- Coals with the highest volatile matter content and the highest free-swelling index had the highest levels of particulate and POM emissions.
- Anthracite (a naturally smokeless coal) was the only coal investigated that could be burned with a uniform flame. This coal generated the lowest smoke, particulate, and POM emissions.
- The processed smokeless coal was effective in achieving low smoke and POM emissions. However, this coal was soft and broke into an excessive amount of fines when fired, thus producing an unexpectedly high particulate loading. It is anticipated that this problem can be overcome by utilizing a suitable binder.
- Significant reduction in particulate and POM emissions were achieved for the high volatile bituminous coal with minor modifications in the design and operation of the stoker. These same modifications were ineffective in reducing emissions from the Western subbituminous coals.

- POM emissions generated from steady-state firing of the stoker were significantly higher than those generated from steady-state operation of oil-fired equipment. In addition, compared to oil combustion, a greater percentage of the POM compounds generated from stoker coal firing are considered to be potentially carcinogenic.

- Higher particulate loadings were generated during the "off" cycle than during the "on" for the coals having volatile matter contents greater than 20 percent.

Stoker Survey

After surveying over twenty present or past manufacturers (or their representatives) of residential and small commercial stoker-fired space heating equipment, it was concluded that:

- Stoker technology has not advanced in the past 25 years as the declining market could not justify stoker R&D.

- There has been renewed interest in stoker firing in the size ranges of interest. The majority of interest has been for small commercial applications rather than for residential installations.

- Where gas and oil are not available, residential space heating is accomplished by electric heat resistance heating rather than stoker firing.

- Residential and small commercial stoker-boilers are similar in design as system components are scaled (up or down) to match the desired range of operation. The stokers are of the underfeed type.

- The conventional underfeed anthracite stokers are designed to fire anthracite only. Because anthracite burns to an easily handled powderlike ash, some underfeed anthracite stoker designs include automated ash removal.

- Only one manufacturer of the conventional bituminous stoker in the size range of interest could be identified. This manufacturer sells about 500 units/yr in the U.S., mainly as replacement units. These stokers are generally installed in rural communities.

- Only one manufacturer of the conventional anthracite stoker in the size ranges of interest could be identified. This manufacturer sells only a few units per year.

- The majority of new stoker-boiler systems are designed for hot water, while most replacements are for steam systems. There has been some renewed interest in stoker-fired warm-air furnaces, but no significant amount of sales.

- The cost of the stoker itself is a significant portion (almost half) of the overall cost of the stoker-boiler system. Gas and oil burners in this size range are significantly less expensive than stokers.

Smokeless Coal Survey

The findings from the survey of processed smokeless fuels include:

1. There is currently no significant market for processed "smokeless" stoker fuels.

2. There are currently no commercially available processed "smokeless" coals suitable for stoker firing. Only one smokeless fuel plant operating on a commercial scale in the United States was identified. This plant markets a briquet suitable for hand firing.

3. The technology exists to manufacture a processed smokeless coal suitable for stoker firing.

4. The brief survey of environmental impact of smokeless coal process plants suggests that process emissions can be controlled with current emission control technology.

SECTION 4

ASSESSMENT OF THE RESULTS

Several factors can be defined that would enhance the market position of small stokers, as follows:

- An increased concern over the continued availability (and price) of natural gas and fuel oil
- Further stoker development: the experimental investigation suggests that stoker firing can become more environmentally acceptable through changes in design and operation of the stoker
- Availability of suitable stoker fuels: it appears that a process coal can be manufactured that would enhance the acceptability of stoker firing.

However, in spite of these factors, the current economic and environmental considerations, along with the inconvenience associated with coal firing, make widespread stoker use unattractive.

SECTION 5

RECOMMENDATIONS FOR FUTURE WORK

It is recommended that future research on small stokers be focused on making stoker firing a more acceptable and competitive method of space heating by (1) determining the necessary practical modifications in the design and operation of stokers to reduce emissions and eliminate operating problems (cakings, etc.), and (2) identifying and evaluating suitable processed or treated coals. The minor modifications in the stoker design and operation considered in this program showed promise and other (major) modifications should be investigated. Recently developed processed or treated low-sulfur coals, such as those developed by TRW (Meyer's Process) and Battelle-Columbus (hydrothermally treated) should also be considered for stoker firing. In addition, a processed coal with a limestone binder (similar to those used in Korea during the 1950's) offers promise for SO_2 control. Furthermore, in any future work, it is recommended that additional pollution measurements and corresponding analyses (as in EPA's Level 1/Level 2 Methodology) be conducted to provide a complete characterization and evaluation of coal types and system modifications.

SECTION 6

BACKGROUND ON STOKER DESIGN AND OPERATION

Smoke evolved when burning high-volatile coal has always been a problem for residential and small commercial heating units. Development of the residential underfeed stokers, such as the inverted-underfeed stoker designed by Battelle in the 1940's, made it possible to burn high-volatile coal smokelessly. However, recent attention has focused on all emissions, which includes not only smoke but NO_x, SO_x, CO, CO, particulate, and POM. Levels of the individual emissions are related to stoker design, stoker operation and firing procedure, and/or the type of coal burned. These aspects are discussed below.

Stoker Design

The small mechanical stokers in the range of interest are of the underfeed type with a worm-feed mechanism. This type of stoker is used for firing coal at rates up to about 1200 lb/hr (550 Kg/hr). In contrast to hand firing or spreader stokers, underfeed stokers supply fresh coal to the boiler or furnace by feeding it underneath the hot coals. The underfeed stoker consists of a retort, blower, air duct, air duct control, feed screw, motor and transmission. Figure 1 is an illustration of a typical stoker assembly.

Retort--

The retort is a cast-iron chamber in the shape of a cup or trough in which the coal is devolatized and ignited. The retort is surrounded by a windbox and contains slotted holes for admitting air under slight pressure to the fire. These slotted holes, or air admitting ports, are often referred to as the tuyeres.

Feed Screw--

The feed screw conveys the coal from the hopper to the retort, or with a bin-fed type, directly from the coal bin to the retort. The feed screw extends from the coal supply (hopper or bin) through the coal-feed tube into the retort, where it discharges the coal it conveys.

Blower and Air Control--

Blowers for supplying combustion air in the underfeed stokers are usually squirrel-cage types that provide relatively high pressures and low volumes. The blower is equipped with either a manual or automatic damper to regulate air flow. The blower develops sufficient static pressure to overcome a series of resistance generated by flow through the regulating damper, air duct, tuyeres, and fuel bed.

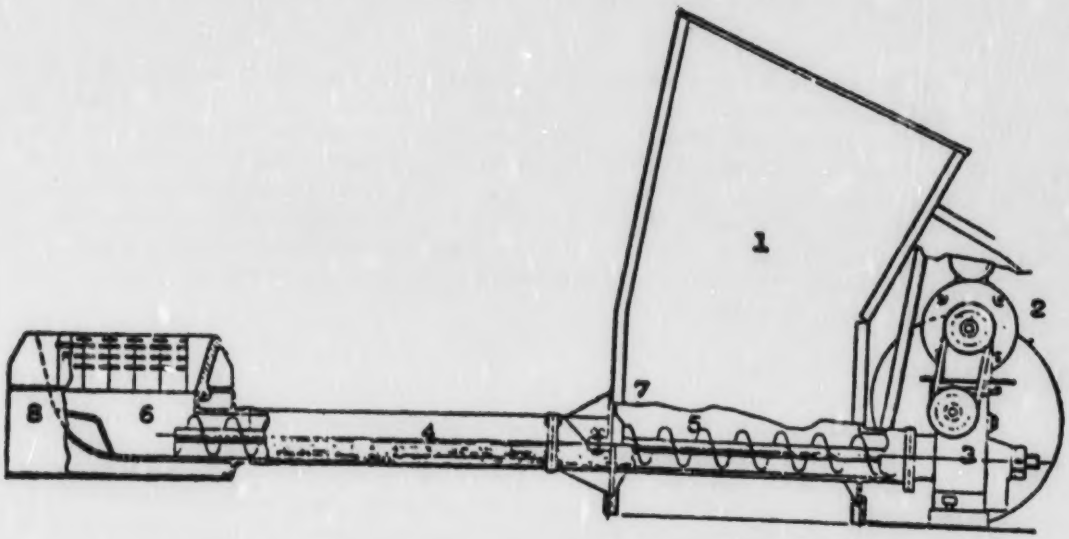

FIGURE 1. Conventional stoker assembly.

Side illustration showing various parts:

1. Hopper
2. Electric motor
3. Transmission
4. Coal feed tube
5. Feed worm
6. Retort
7. Clean out opening
8. Retort air chamber.

Motor and Transmission--

The coal-feed screw is driven by an electrical motor, usually mounted on top of the transmission. The motor drives the transmission through V-belts. Operation of the motor is controlled by various electrical devices including room thermostat, boiler limit switch, and the hold-fire timing relay. The transmission rotates the coal-feed screw; the rotational speed of the feed screw is determined by the capacity of the heating system. Feed rates can be varied by changing either the screw ratchet setting or transmission pulleys.

Stoker Operation

The residential and small commercial stoker-boilers operate basically the same in principle although their operating cycles can be different depending upon application. Characterization of the operation of these units is complicated because they seldom operate with a steady-state heat-release rate.

Off-On Cycle--

Small stokers operate in an off-on cycle. When "on" (feed screw operating) the stoker always feeds coal at a constant rate, it adjusts to varying loads by varying the percent "on" time in each cycle. During the "on" time, fresh coal is fed underneath the hot coals and air is admitted through the tuyeres. The heat-released rate increases substantially as the fuel bed temperatures gradually increase. Fuel bed temperatures often do not reach a steady-state temperature before the thermostat stops the stoker screw and fan. Upon shutdown the fuel bed continues to burn, but the heat-release rate is reduced drastically as the bed is being supplied by minimal quantities of air by the natural draft. At this time unburned hydrocarbons can be released because of insufficient air. Figure 2, a plot of CO_2 levels as a function of time, illustrates the nonsteady heat-release rate of stokers (1).* Figure 3 shows a typical plot of retort and stack temperatures during continued cyclic operation of a stoker on a 10-minute on and 50-minute off cycle (2).

Full-Load and Hold-Fire Operating Cycles--There are two extremes in stoker-boiler operation, namely, full-load and no-load. During full-load operation, the stoker is running continuously; however, the stoker is stopped for at least 5 minutes in every 30-minute cycle so that bed temperatures cool and the ash fuses. (The "off" time can vary with ash content composition of the fuel. Anthracite with a low ash content and high fusion temperature can be burned continuously with no "off" period.) If not given an opportunity to cool, the ash may remain fluid and sticky forming agglomerated massive clinkers with resulting nonuniform feeding and irregular burning.

During the no-load period, the boiler operates in a "hold-fire" mode of operation. In the hold-fire mode, the stoker is fired for short periods to keep the fuel bed sufficiently alive to respond quickly when the boiler load increases, otherwise the fuel bed temperature will be too low to ignite fuel that enters the retort during the next on-period. The typical hold-fire period for bituminous coal is approximately a 5-minute operation of the stoker in each 30 minutes. (The hold-fire period for anthracite can be as low as one minute every half hour.) Partial load operation falls in between these extremes.

* References are listed on page 76.

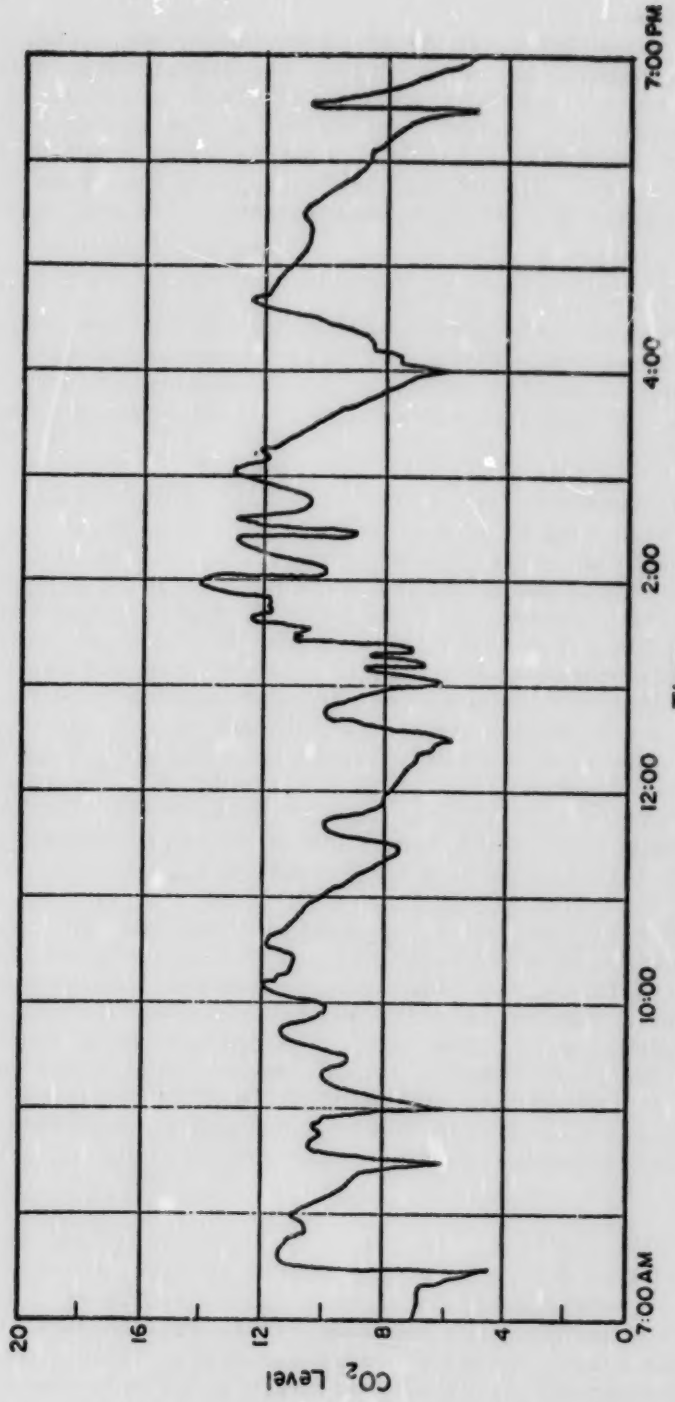

FIGURE 2. Typical record of CO_2 content of flue gases from a small stoker operating under intermittent control.

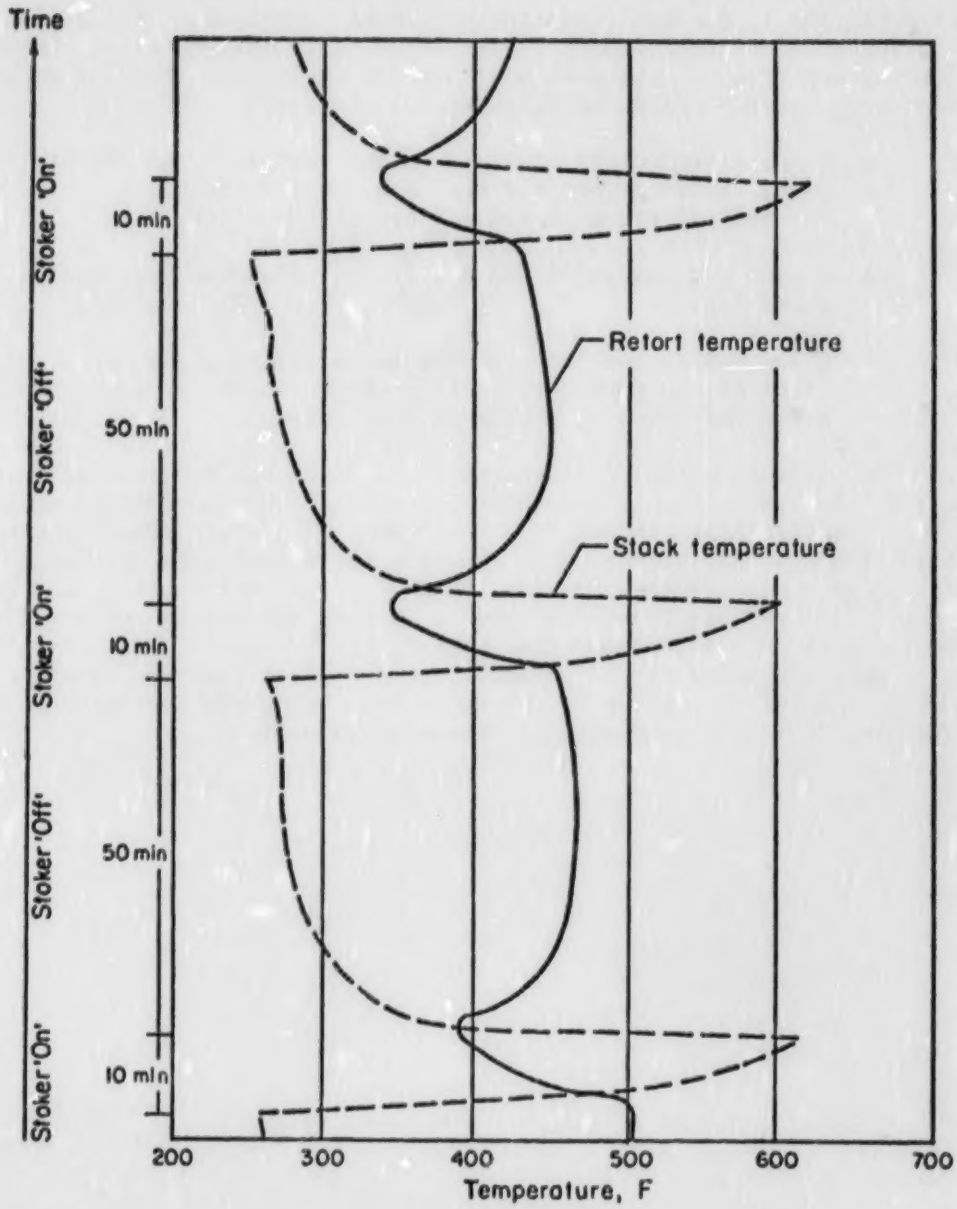

FIGURE 3. Typical plot of retort and stack temperature during cyclic operation (10-minutes-on and 50-minutes off).

Coal Selection

Selection of stoker coals is of paramount importance in successful stoker operation. (In today's environmentally aware society, successful stoker operation is generally equated to proper operation of the stoker without visible smoke emissions.) Proper stoker adjustments for smokeless operations are largely dependent on the coal analysis and coal size. For instance, unsatisfactory stoker operation (high smoke) occurs if

- A large percentage of fines either restricts the amount of air that reaches the fuel bed, or the fines are carried off the fuel bed and out of the stack.
- A high percentage of ash results in troublesome clinker formation.
- A low ash-fusion point coal creates clinkers that are difficult to remove from the stoker because the ash melts and fuses or sticks to the tuyeres.

Accordingly, the most desirable coals for small stoker operation are relatively free-burning, low-volatile, low-ash and low-sulfur coals that are sized 3/4 x 1/4 inches (1.9 x 6.4 mm). The free-burning coals include all coals that do not cake. (Caking coals emit tars and swell when heated.) These coals burn to a fine ash and do not restrict air flow through the fuel bed. Low volatile coals tend to burn slowly with a uniform flame and as a consequence do not generate appreciable levels of smoke over the entire stoker operating cycle. Finally, sulfur oxide emission levels are related to the sulfur content of the fuel, and, thus, the low sulfur coals are the most desirable from the environmental viewpoint.

SECTION 7

PLAN OF EXPERIMENTAL INVESTIGATION

Five candidate stoker coals were evaluated in a 20-hp (200 kW) commercial boiler. The majority of research was conducted at one boiler operating cycle and at a moderate boiler load of about 22 percent of rated full-load capacity. [Operating load is determined by two factors: firing rate during the "on" time and percent "on" time. Thus, a unit rated at 75 lb/hr (34 kg/hr) but fired at 50 lb/hr (22 kg/hr) for a 20-minute-on/40-minute-off cycle would operate at a load of 22 percent (50/75 x 20/60 x 100).] A limited number of experimental runs were conducted at other boiler cycles and boiler loads. Emissions of primary interest were smoke, particulate, and POM while those of secondary interest included SO_2, CO, and NO.

EXPERIMENTAL FACILITY

Overall System

Figure 4 is a photograph of the overall system layout that was used for the stoker research. This system includes:

- Kewanee 3R-5, 20-bhp (200 kW), fire-tube, hot-water boiler
- Will-Burt 75 lb/hr (34 kg/hr) bituminous stoker
- 14-in. (0.35 m) diameter stack section
- Sampling platform.

A Van Wert 60 lb/hr (27 kg/hr) anthracite stoker (not shown) was also used to fire the boiler for selected runs. These two stokers were selected as they were the only commercially available stokers in the size range of interest.

Approximately 10 pipe diameters above the boiler stack-gas outlet, 4 sampling ports were installed. These ports were utilized to sample during discrete time periods of stoker-boiler operation. Approximately 5 feet (1.5m) above the sampling ports a damper was installed to provide a control of the draft at the boiler outlet. Ports for smoke and gaseous-emission sampling and for temperature and pressure measurements were provided at the base of the stack.

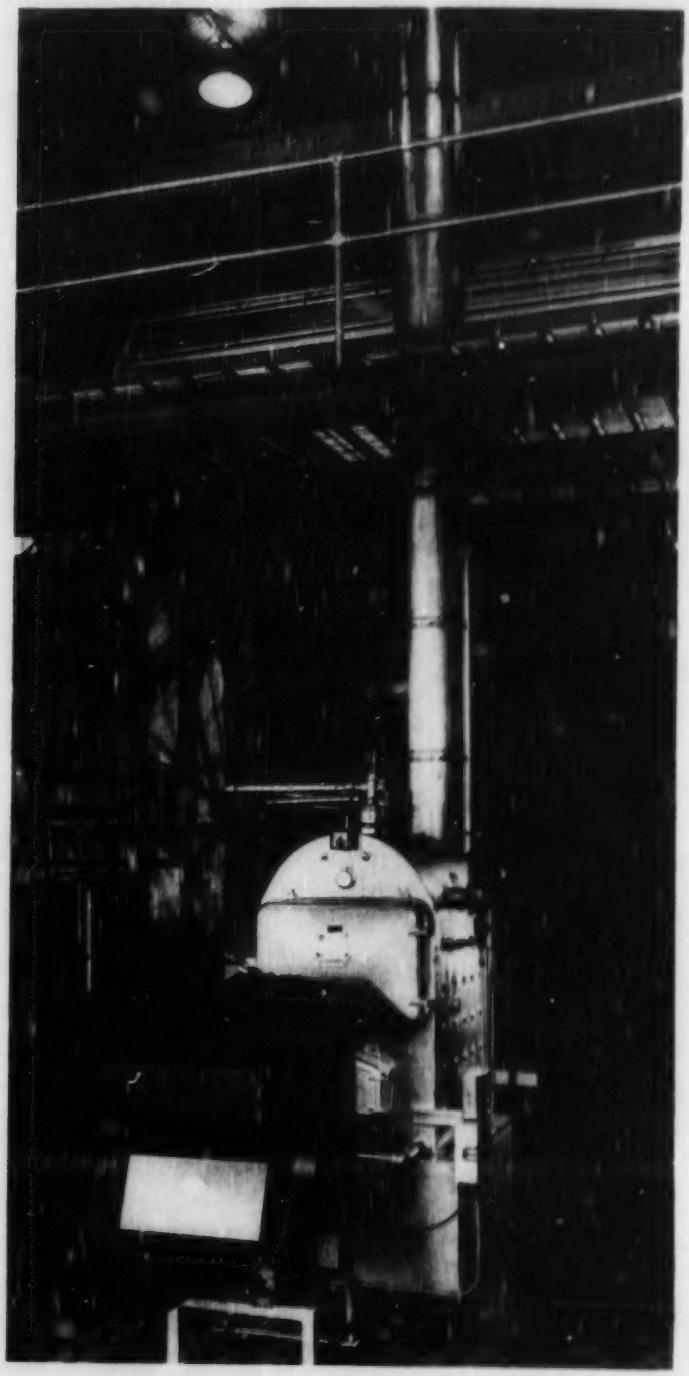

Figure 4. Stoker-fed boiler facility

Stokers

Bituminous Stoker--

The Will-Burt 75 lb/hr (34 kg/hr) stoker is a conventional bituminous underfeed stoker. The majority of coal is burned in the retort with the remaining coal being burned on a ceramic hearth surrounding the retort. In srokers of this size, there is no provision for automatic removal of ash.

The Will-Burt stoker is supplied with a 3-groove pulley that is used to control the coal feed rate. The coal feed screw and blower are driven with the same motor. Air flow rate is controlled by a damper on the blower inlet. During the checkout of the facility, it was observed that the blower did not have sufficient capacity, even at the lower firing rates. As a consequence, the blower was removed and the laboratory compressed air line was used to supply the combustion air. The air flow rate was measured with a standard ASME orifice.

Over-fire air jets are not normally included as part of the stoker-boiler furnace. However, 4 air jets [6 in. (0.15 m) on center] 0.28 in. (7 mm) in diameter were installed approximately 12 in. (0.31 m) above the retort. The overfire or secondary air flow rate, approximately 10 to 15 percent of the underfeed or primary air flow rate, was measured with a rotameter.

Anthracite Stoker--

The Van Wert stoker is a conventional anthracite underfeed stoker. This particular design did not include provision to vary the coal feed rate. Combustion air was supplied by a fan that was directly coupled to the stoker motor. Air flow could be modulated by a damper on the fan inlet. With this stoker, the anthracite was completely burned within the retort and the ash would fall to a pit below the retort. This dry, powderlike ash would not interfere with the combustion or air distribution.

COAL SELECTION AND ACQUISITION

Coals were selected to provide a range of fuels representative of residential and small commercial stoker utilization.

Basis for Selection

Because of the vast number of candidate stoker fuels, guidelines compatible with the overall objectives of this program were established to restrict the number of potential coals. These guidelines included:

- Geographical source of each fuel should represent a substantial availability for residential and commercial use of the representative type.
- The processed smokeless fuel should be obtained from a commercially operated process.

- Natural smokeless coals should be selected for comparison with the processed fuel.
- Coals of dissimilar characteristics should be selected to represent fuels not considered smokeless.
- Shipping distance should be chosen to minimize transportation costs.
- All fuels should be obtained in a size suitable for stoker firing.

Accordingly, the following five coals were identified and procured in approximately 1.5 ton (1.5 metric ton) quantities.

Processed Smokeless Fuel--

Lignite char briquettes were procured from Husky Industries of Dickenson, North Dakota. These briquettes required crushing and double screening [1 x 1/4 in. (25 x 6.4)] as they were pillow-shaped, similar to a charcoal briquette. A corn flour binder had been used that appeared to be unsuitable for stoker firing. During the crushing and screening, it was observed that the coal was soft and crumbled easily. Only 40 percent of the original briquette remained in the desired size range after screening.

Anthracite--

Because of its low volatile content, anthracite was considered as a natural smokeless fuel. An experimental lot of Number 1 Buckwheat [9/16 x 5/16 in. (14 x 7.9 mm)] Pennsylvania anthracite was procured through Blue Coal Corporation of Wilkes-Barre, Pennsylvania.

Low-Volatile Bituminous--

This coal is also considered a natural smokeless coal because of its relatively low volatile content for a bituminous coal. A quantity of stoker [1 x 3/8 in (25 x 9.5 mm)] Pochantas Seam 3 coal from the Bishop Mine, in Bishop, West Virginia was procured.

High-Volatile Bituminous--

The high-volatile bituminous coal procured was an Elkhorn Number 3 Seam coal from the Poly Mine at Irvine, Kentucky. The coal size was about 1-1/4 x 1/4 in. (32 x 6.4 mm).

Western Subbituminous--

This coal was mined from the Black Diamond Seam of the Corely strip mine in Fremont County, Colorado. This stoker coal was air-cleaned and sized to 1-1/4 x 5/8 in (32 x 16 mm).

Fuel Analysis--

Table 1 lists properties of the coals that were fired during this program. The analyses are reported on an "as received" basis and include the moisture content of the coals. This moisture content can vary randomly from day to day, depending on climatic condition, and is also dependent

TABLE 1. COAL ANALYSIS

Coal	Proximate Analysis, percent				Elemental Analysis, percent			Free Swelling Index[a]	Heating Value,[b] Btu/lb
	Fixed Carbon	Volatile Matter	Ash	Moisture	C	H	S		
High volatile bituminous	53.5	40	4.7	1.8	79.5	5.7	1.2	5	14,100
Low volatile bituminous	70.8	21.4	6.9	0.9	84.7	4.7	0.6	7.5	14,700
Western sub-bituminous	45.4	37.4	9.2	8.0	64.6	4.2	0.6	0.5	11,400
Processed lignite char	61.6	16	15.1	7.3	67.9	1.7	0.6	0	10,600
Anthracite	71.5	3.9	12.3	12.3	79.4	2.0	0.7	0	11,900

(a) A high value is indicative of a highly caking coal.

(b) 1 Btu/lb = 2326 J/Kg.

upon washing procedures used at the mine. In general, however, the moisture content gives a measure of the inherent moisture content of the coal. The free-swelling index is a measure of the caking properties of the coal, as indicated by high values of the caking bituminous coals.

EXPERIMENTAL RUNS AND OPERATING CONDITIONS

Gaseous and Smoke Characterization Runs

Initially, each coal was characterized by making gaseous and smoke emission measurements as a function of excess air for several firing rates and boiler operating cycles to determine the range of smokeless operation. Smokeless operation was defined as no visible smoke in the stack gas as determined by visual observation. Once these conditions were established, the boiler stack was probed to generate transient temperature and velocity profiles to establish appropriate sampling rates for particulate and POM sampling.

Evaluation Runs

As can be seen from Figure 2, for most coals, a stoker operating under intermittent operation seldom burns with any uniform and repeatable pattern -- the result of a continuously changing fuel bed. Accordingly, to provide some measure of control of the fuel bed, when making emission measurements, before emission sampling was begun, the stoker was operated sufficiently long to establish a stable fuel bed, but not so long that ash buildup and/or clinker formation would significantly interfere with the performance of the stoker. Thus, emission measurements were made at comparable, but relatively optimum, stoker firing conditions, rather than at conditions representative of practical or typical operation.

Firing Rates

Although the stoker-boiler system was designed for a 75 lb/hr (34 kg/hr) firing rate, at this firing rate, the coal flames (except anthracite) would impinge upon the boiler crown sheet causing quenching of the flame and smoke formation. As a consequence, firing rates were reduced to about 45 to 55 lb/hr (20 to kg/hr), except for anthracite that could be successfully fired at 67 lb/hr (30 kg/hr). In addition, it was necessary to fire with overfire air for the high- and low-volatile bituminous coals as well as for the Western subbituminous coal to achieve smokeless operation. For anthracite and the process smokeless coal, both lower in volatile matter, overfire air was not required to achieve smokeless operation.

For the high-volatile bituminous and Western subbituminous coals, firing at rates of about 23 and 75 lb/hr (10 to 34 kg/hr) during the "on" time were also investigated. (Residential and small commercial designs generally include provision to adjust the feed rate for about one-third, two-third, and full load.)

Boiler Operating Cycles

In an investigation of emissions from small commercial oil- and gas-fired furnaces (3), an operating factor of 1/3 (10-minutes-on/20-minutes-off cycle) was considered as typical. Accordingly, for comparison purposes, several cycles which would provide a 1/3 operating factor were considered. It was observed that when operating the boiler on a 10-minutes-on/20-minutes-off cycle, the fuel bed began to degrade after a few cycles. The degradation was attributed to incomplete combustion of raw coal rather than ash buildup or clinker formation. This was especially noticeable for the low-volatile bituminous coal. Increasing the length of the cycle from 30 minutes to 60 minutes alleviated this problem. Therefore, a 20-minutes-on/40-minutes-off cycle was selected as the basic cycle to evaluate the emissions from the firing of each coal.

The high-volatile bituminous and Western subbituminous coals were also fired on a 50-minute-on/10-minute-off cycle.

EXPERIMENTAL PROCEDURES

Particulate and POM Sampling Procedure

The operating cycle of a stoker-boiler creates a unique problem in obtaining meaningful particulate and POM emissions data. As discussed earlier, the stoker seldom operates at a steady-state condition. Transients occur not only during the starting and stopping of the stoker but throughout each "on" and "off" period of operation. In addition, and most importantly, during the "off" period, the fuel bed continues to burn as a small amount of air is supplied by the natural draft of the stoker-boiler system. Accordingly, the stack flow was characterized to determine transient temperature and velocity profiles throughout the 60-minute cycle. From an integration of these profiles, an appropriate probe position (within the stack) and sampling rate was determined for each period of stoker operation.

Stack Probing--

Hot-wire anemometry was used to characterize stack flow as a function of time as conventional sampling apparatus instrumentation did not have adequate sensitivity or response time. Two hot-wire probes (quartz-coated hot-film sensors with instantaneous response time) were used simultaneously. Probe 1 was located approximately 2 ft below the sampling port and contained a hot-wire sensor set stationary on the centerline to monitor axial flow velocity with time. In addition, a thermocouple was attached to monitor temperature with time. These data were used as a baseline measurement. Probe 2 was used to determine the velocity profile across the duct at the sampling position.

Sampling Period and Rate Determination--

The transient stack-probe data were analyzed to relate the temperature and velocity profiles to stoker-cycle operation. Because these profiles were essentially flat across the 14-in. (0.36 m) diameter stack, sampling was simplified as traversing was not necessary.

Figure 5 is a plot of stack-gas temperature versus time during one 20-minutes-on/40-minutes-off cycle while firing the high-volatile bituminous coal. The stack-gas velocity curve is similar in shape. As shown in Figure 5, the cycle is divided into 4 discrete time periods. These time periods were selected as representative of discrete periods of stoker operation, namely: (1) transient on, or startup, (2) "steady-state" on, (3) transient off or shutdown, and (4) "steady-state" off. The period of each of these discrete time segments was based not only on the time-rate-of-change of stack-gas velocities and temperatures, but also upon the smoke densities within each segment. Generally, during time periods (1) and (3), startup and shutdown, respectively, smoke is visible from the stack for a few minutes, indicating at least a different quality (if not quantity) of the emissions. Accordingly, a separate sampling train was used for sampling during each time segment to provide a relative measure of particulate and POM emission levels for each time segment within the cycle. Furthermore, use of four sampling trains permitted a more accurate approach to isokinetic sampling than could be achieved with one or two trains.

Because temperature and velocity were rapidly changing within some segments of the cycle (especially during startup and shutdown), it was determined that the sampling rate could not be continually adjusted to provide true isokinetic sampling. Therefore, hot-wire anemometer measurements (both velocity and temperature) were integrated over each time segment to determine an average velocity and temperature and, thus, an average sampling rate for each segment. The nozzle of each train was pointed upstream only when a sample was being drawn; otherwise, they were rotated 180° so that they pointed downstream. To obtain a representative sample, measurements were made over 4 to 6 cycles. This required that each probe be rotated 8 to 12 times during a run. During the later runs of the program, only two trains were used, one for the "on" period and the other for the "off" period.

Analytical Procedures

Particulate and POM levels were determined by a modified EPA Method 5 procedure with the probe wash and filter catch being used to determine the filterable particulate loadings and an adsorbent column being used to determine POM loadings (4).

Gaseous emissions were determined by: paramagnetic analysis for oxygen; flame ionization detection for unburned hydrocarbons; nondispersive infrared for carbon monoxide, carbon dioxide, and nitrogen oxide; and a dry electrochemical analyzer for sulfur dioxide. Smoke emissions were determined with a Bacharach smoke tester according to the ASTM filter-paper method for smoke measurements (5). Although it is realized that this method of smoke determination was developed for distillate oil-fired systems and not coal-fired systems, it provided a quick, convenient determination of the relative levels of smoke.

Feed-Rate Determination

The coal feed rate for each stoker was determined by weighing the amount of coal that was required to refill the stoker hopper after the stoker was operated for some specific time period. This procedure determined an average coal feed rate and not an average burning rate.

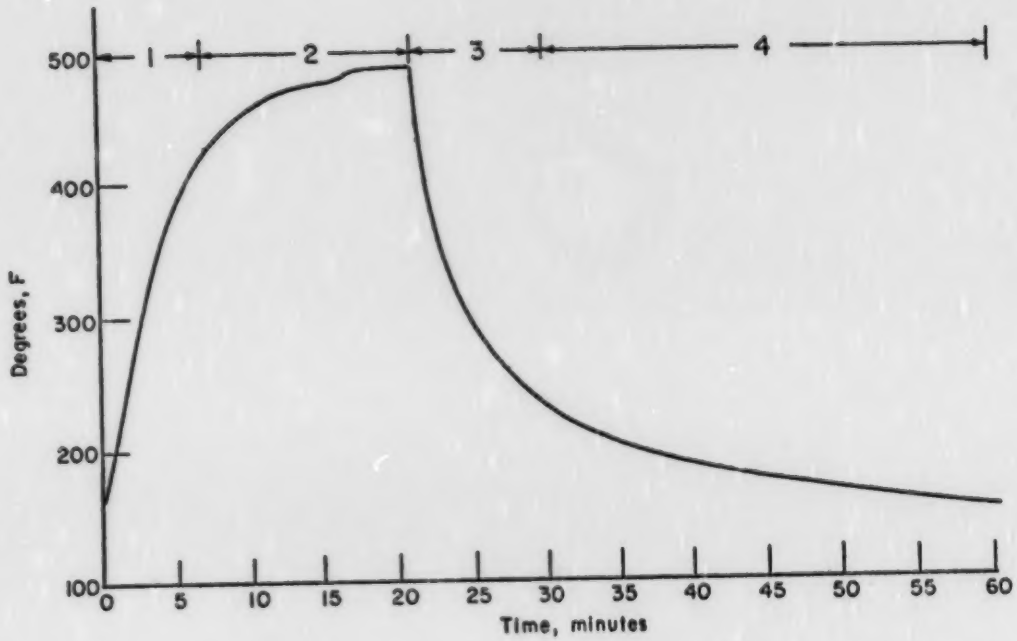

FIGURE 5. Stack-gas temperature as a function of time indicating the four discrete time periods for sampling.

SECTION 8

EXPERIMENTAL RESULTS

The performance of the stoker and the emissions that it generates are dependent upon a number of factors that include the properties of the coal and combustion operating parameters. Coal properties can be defined in reasonably precise terms using ASTM procedures. Conversely, while there are some measurements to characterize combustion conditions (e.g., CO_2 and O_2 in the flue gas, coal firing rate, etc.), there are few measurements to characterize the fuel bed other than visual observations and/or photographs. Hence, these qualitative observations are necessary to provide a description of the fuel-bed combustion. Accordingly, in addition to experimental measurements tabulated in Tables 2, 3, and 4, visual observations of fuel bed conditions are included in the interpretation of the data.

Table 2 summarizes the stoker operating conditions and the gaseous, smoke, particulate, and POM emissions generated during the firing of the five different stoker coals for the conditions listed. Because stoker combustion conditions are rarely a true steady state, the gaseous emission levels shown during Time Segments 1 and 2 indicate the range of these emissions during the on-period of operation, while those shown in Time Segments 3 and 4 indicate the range during the off-period. Because it was observed during the early runs that the particulate and POM emissions were not appreciably different between Time Segments 1 and 2 and also between 3 and 4, only two trains, one for the "on" period (Time Segments 1 and 2) and the other for the "off" period (Time Segments 3 and 4) were used during the later runs.

TABLE 2. SUMMARY OF EXPERIMENTAL DATA

Run	Coal	Cycle, on/off min.	Load,[a] percent	Firing Rate,[b] lb/hr	Air Flow Rate Prim. lb/hr	Air Flow Rate Sec. lb/hr	Gas Analysis O_2, percent	Gas Analysis CO_2, percent	Gas Analysis SO_2, ppm	Gas Analysis NO, ppm	Gas Analysis CO, ppm	Bacharach Smoke	Particulate and FDM Sampling Time Segment	Particulate and FDM Sampling Length of Time Segment, Min.	Particulate and FDM Sampling No. of Segments Sampled	Particulate Results Total, mg	Particulate Results Loading mg/Nm³	FDM Results Total, mg	FDM Results Loading mg/Nm³
1	High-volatile bituminous	20/40	19	42	500	50	4.6-11.6	8.5-14.6	600-800	160-200	165->1250	5-≥9	1	5	6	34.7	110	4.6	13.9
				0	0	0	13.9-15.8	4.6-6.0	360-420	55-60	>1250	≥9	2	15	6	116.6	110	7.1	6.5
													3	6	6	700.3	1400	4.5	9.0
													4	34	1[c]	248.6	2400	3.0	28.7
2	High-volatile bituminous	20/40	20	44	500	50	5.4-8.5	11.6-14.3	510-750	200-240	60-100	6-≥9	1	5	4	40.6	160	2.5	9.8
				0	0	0	12.0-18.5	2.4-3.6	150-180	30-40	>1250	≥9	2	15	7	218.4	200	9.3	8.2
													3	6	7	910.4	1600	12.8	23.0
													4	3	1[c]	198.5	810	4.2	17.2
3	High-volatile bituminous	50/10	49	44	500	50	5.0-6.5	15.2-16.5	630-900	600-900	40-100	7-≥9	1	7	3	119.6	110	8.6	7.6
				0	0	0	10.5-12.8	8.0-9.8	500-580	60-100	>1250	≥9	2	43	6	367.7	100	6.7	1.8
													3	10	6	760.7	1300	16.5	28.7
4	Processed	20/40	20	45	450	0	8.0-12.5	8.6-11.0	170	120	100->1250	4-5	1	6	6	217.2	290	0.24	0.33
				0	0	0	12.0-18.5	2.4-3.6	30-40	20-30	>1250	1-2	2	14	6	623.4	390	0.17	0.11
													3	8	6	42.3	44	0.09	0.09
													4	32	6	12.5	4	0.19	0.66
5	Western	20/40	24	55	640	60	10.5-12.3	8.1-9.8	210-270	120-130	560-850	2-4	1	6	6	38.9	66	0.87	1.5
				0	0	0	14.1-18.5	2.4-2.6	30-40	< 40	>1250	≥9	2	12	6	58.5	73	1.5	1.1
													3	10	6	42.2	52	1.3	1.6
													4	30	5	285.5	110	3.5	1.5
6	Low-volatile bituminous	20/40	23	52	610	60	5.5-11.0	8.0-16.0	--	120-170	<80	3-4	1	7	6	120.7	180	0.39	0.57
				0	0	0	11.0-15.8	4.6-9.0	--	30-50	>1250	7-≥9	2	13	6	174.9	120	1.8	1.1
													3	8	6	298.1	390	16.7	22
													4	32	3	231.1	190	7.8	6.4
7	Western	20/40	23	52	660	53	10.7-12.4	8.4-10	--	--	40-80	4-6	1&2	20	6	73.72	37	--	--
				0	0	0	15-18	1.8-2.2	--	--	>1250	≥9	3&4	40	6	313.8	99	--	--
8	High-volatile bituminous	20/40	19	43	580	50	7-10	9.4-11	--	--	40-160	--	1&2	20	6	189.1	110[d]	--	--
				0	0	0	12-15	4.1-6.7	--	--	>1250	--	3&4	40	6	394.2	390	--	--
9	Anthracite	20/40	30	67	fan	0	10-12.6	8.4-10	200-240	30-40	150-≥ 80	1/2	1	5	5	26.8	84	0.112	0.35
				0	0	0	16-17	3.3-3.7	60-100	10-15	>1250	1/2	2	15	5	73.8	70	0.157	0.15
											>1250	1/2	3	10	5	23.7	26	0.0200	0.022
											>1250	1/2	4	30	5	13.5	5.3	0.0301	0.012
10	Anthracite	50/10	74	67	fan	0	7-10	9.6-12.5	240-280	60-90	30-640	0	1	5	6	63.5	160	0.0565	0.14
				0	0	0	13-15	6-8	130-150	30-40	>1250	1/2 0	2	35	6	617.9	160	0.325	0.008
													3	10	6	53.5	54	0.107	0.11
11	Western	20/40	10	23	350	0	12.5-15.5	2.0-7.8	120-180	80-100	150->1250	6->9	1&2	20	5	76.9	45	0.92	0.53
				0	0	0	14.5-18.3	1.9-3.0	50-100	10-30	>1250	>9	3&4	40	6	194.9	61	0.69	0.22
12	High-volatile bituminous	20/40	33	75	760	75	4-6	13-13.8	--	200-250	40-80	4->9	1&2	20	5	233	120	1.6	0.81
				0	0	0	14-15	4.2-5.6	--	40-70	>1250	≥9	3&4	40	5	1838	610	1.0	0.33

TABLE 2. (Continued)

Run	Coal	Cycle, on/off min.	Load, percent	Firing Rate, lb/hr	Air Flow Rate Prim. lb/hr	Air Flow Rate Sec lb/hr	Gas Analysis O_2, percent	Gas Analysis CO_2, percent	Gas Analysis SO_2, ppm	Gas Analysis NO, ppm	Gas Analysis CO, ppm	Bacharach Smoke	Particulate and POM Sampling Time Segment	Particulate and POM Sampling Length of time Segment, min.	Particulate and POM Sampling No. of Segments Sampled	Particulate Results Total, mg	Particulate Results Loading, mg/Nm³(5)	POM Results Total, mg	POM Results Loading, mg/Nm³
13	High-volatile	20/40	10	23	350	40	10-13	6.5-7.9	--	120-170	>1250	>9	162	20	5	232	130	0.46	0.26
				0	0	0	15-17	3.5-4.5	--	40-70	>1250	>9	364	40	5	600	190	0.57	0.18
14	Western	20/40	11	25	400	40	12-14	6.3-9.0	--	100-130	100-140	5-9	162	20	5	86.7	50	0.76	0.44
				0	0	0	16-18	2-4	--	40-60	>1250	>9	364	40	5	31.7	94	0.56	0.17
15	Western	20/40	33	75	880	85	5-7	13.4-14.8	280-500	150-190	20-40	4-6	162	20	--	1396	77	0.41	0.23
				0	0	0	14-18	2-5	80-100	25-50	>1250	>9	364	40	--	651	160	2.5	0.60
16	Western	(c) 20/40	22	50	600	60	9.5-12.8	7.1-10-2	190-240	100-140	50-150	3-5	162	25	5	93.5	37	2.5	0.98
				0	0	100	15.5-18.2	1.9-5.2	40-90	40-9	>1250	6->9	364	35	5	300	87	2.0	0.58
17	High-volatile	(e) 20/40	20	45	550	60	9.5-11	7.6-9.6	--	220-280	100-200	8-9	162	25	4	165	93	3.0	1.7
				0	0	100	15+17.5	2.6-3.8	--	50-80	>1250	>9	364	35	3	517	290	3.3	1.9

(a) Load is given in percentof continuous rated-load operation.

(b) Lb/hr = .454 Kg/hr.

(c) Partial segment.

(d) Broken frit.

(e) Modified cycle: During the first 5 minutes of the "on" cycle, the primary air flow was only 200 lb/hr. In addition, during the first 5 minutes of the "off" cycle, the secondary (overfire air jets) remained on to help reduce smoke.

TABLE 3. EMISSION FACTORS FOR THE FIVE STOKER COALS

Run	Coal	Cycle, on/off, min.	Firing Rate, lb/hr(a)	Bacharach Smoke		Particulate Loading		PCM Loading		Particulate Emissions, g/lb coal fed	PCM Emissions, mg/lb coal fed
				On-Cycle	Off-Cycle	On-Cycle, mg/Nm^3	Off-Cycle mg/Nm^3	On-Cycle, mg/Nm^3	Off-Cycle, mg/Nm^3		
1	High-volatile bituminous	20/40	42	5->9	>9	110	1600	8.2	13	3.9	86
2	ditto	20/40	44	6->9	>9	190	1400	8.8	21	4.1	82
8	"	20/40	43	6->9	>9	110	590(a)	--	--	--	--
17	"	20/40(b)	45	8-9	>9	93	290	1.7	1.9	1.7	12.3
12	"	20/40	75	4->9	>9	120	610	.81	.33	2.1	8.8
13	"	20/40	23	>9	>9	130	190	.26	.18	3.4	5.4
3	"	50/10	44	7->9	>9	100	1300	3.2	29	0.85	23
5	Western subbituminous	20/40	55	2-4	>9	50	99	1.2	1.5	0.50	10.2
7	ditto	20/40	52	4-6	>9	37	99	--	--	0.43	--
16	"	20/40(b)	50	3-5	6->9	37	87	0.98	0.58	0.60	11.1
15	"	20/40	75	4-6	>9	77	160	0.23	0.60	1.0	3.4
11	"	20/40	23	6->9	>9	43	61	0.53	0.22	1.0	8.3
14	"	20/40	25	5-9	>9	50	94	0.44	0.17	0.77	7.3
6	Low-volatile bituminous	20/40	52	3-4	7->9	140	260	1.0	12	1.4	27
4	Processed lignite char	20/40	45	4-5	1	360	13	0.17	0.68	3.2	1.8
9	Anthracite	20/40	67	0.5	0.5	73	11	0.12	0.15	0.33	0.86
10	Anthracite	50/10	67	0	0.5	160	54	0.21	0.11	0.70	0.12

(a) Broken frit.

(b) Modified.

TABLE 4. POM ANALYSIS

Component	NAS Notation	Run No. 1 Time Segment: 1 mg	1 mg/Nm^3	2 mg	2 mg/Nm^3	3 mg	3 mg/Nm^3	4 mg	4 mg/Nm^3
Anthracene/Phenanthrene		1.30	3.9	2.44	2.2	0.63	1.3	0.57	5.5
Methyl anthracenes		0.74	2.2	1.04	1.0	0.29	0.6	0.43	4.1
Fluoranthene		0.53	1.6	1.43	1.3	0.85	1.7	0.33	3.2
Pyrene		0.41	1.2	0.92	0.8	0.53	1.1	0.23	2.2
Methyl Pyrene/Fluoranthene		0.64	1.9	0.34	0.3	0.25	0.5	0.68	6.5
Benzo(c)phenanthrene	***	0.041	0.1	0.071	0.06	0.024	0.05	0.40	0.4
Chrysene/Benz(a)anthracene	*	0.023	0.07	0.36	0.3	0.27	0.5	0.28	2.7
Methyl chrysenes	*	0.14	0.4	0.10	0.09	—	—	0.090	0.9
7,12-Dimethylbenz(a)anthracene	****	—	—	—	—	—	—	—	—
Benzo fluoranthenes	**	0.19	0.6	0.24	0.2	0.99	2.0	0.16	1.5
Benz(a and e)pyrenes	***	0.13	0.4	0.12	0.1	0.65	1.3	0.10	1.0
Perylene		—	—	—	—	—	—	—	—
3-Methylcholanthrene	****	0.081	0.2	—	0.03	—	—	0.07	0.7
Indeno(1,2,3,-cd)pyrene	*	0.043	0.1	0.034	0.03	—	—	0.015	0.1
Benzo(ghi)perylene		0.029	0.09	0.030	—	—	—	0.010	0.01
Dibenzo(a,h)anthracene	***	0.071	0.2	—	—	—	—	—	—
Dibenzo(c,g)carbazole	***	—	—	—	—	—	—	—	—
Dibenz(ai and ah)pyrenes	***	0.018	0.05	—	—	—	—	—	—
POM		4.6		7.1		4.5		3.0	
POM Loading			13.9		6.5		9.0		28.7

TABLE 4. (Continued)

Component	NAS Notation	Run No. 2 Time Segment: 1 mg	1 mg/Nm^3	2 mg	2 mg/Nm^3	3 mg	3 mg/Nm^3	4 mg	4 mg/Nm^3
Anthracene/Phenanthrene		1.02	4.0	4.22	3.7	2.94	5.3	1.03	4.2
Methyl anthracenes		0.53	2.1	1.54	1.4	0.098	0.2	0.57	2.3
Fluoranthene		0.24	0.9	1.41	1.2	1.19	2.0	0.32	1.3
Pyrene		0.18	0.7	0.96	0.8	0.88	1.6	0.22	0.9
Methyl Pyrene/Fluoranthene		0.17	0.7	0.32	0.3	0.94	1.7	0.25	1.0
Benzo(c)phenanthrene	***	0.01	0.04	0.065	0.06	0.17	0.3	0.030	0.1
Chrysene/Benz(a)anthracene	*	0.080	0.3	0.33	0.3	0.89	1.6	0.24	1.0
Methyl chrysenes	*	0.04	0.2	0.065	0.06	0.44	0.8	0.29	1.2
7,12-Dimethylbenz(a)anthracene	****	--	--	--	--	--	--	--	--
Benzo fluoranthenes	**	0.070	0.3	0.019	0.02	1.79	3.2	0.35	1.4
Benz(a and e)pyrenes	***	0.055	0.2	0.090	0.08	1.30	2.3	0.31	1.3
Perylene		--	--	--	--	--	--	--	--
3-Methylcholanthrene	****	0.045	0.2	0.005	0.05	0.64	1.2	0.40	1.6
Indeno(1,2,3,-cd)pyrene	*	0.020	0.08	0.060	0.05	0.26	0.5	0.13	0.5
Benzo(ghi)perylene		0.015	0.06	0.015	0.013	0.41	0.7	0.095	0.4
Dibenzo(a,h)anthracene	***	--	--	--	--	--	--	--	--
Dibenzo(c,g)carbazole	***	--	--	--	--	--	--	--	--
Dibenz(ai and ah)pyrenes	***	--	--	--	--	--	--	--	--
POM		2.4		9.3		12.8		4.2	
POM Loading			9.8		8.2		23.0		17.2

TABLE 4. (Continued)

Component	NAS Notation	Run No. 3 Time Segment: 1 mg	1 mg/Nm^3	2 mg	2 mg/Nm^3	3 mg	3 mg/Nm^3	4 mg	4 mg/Nm^3
Anthracene/Phenanthrene		1.58	1.4	2.25	0.6	1.58	2.7		
Methyl anthracenes		1.06	0.9	1.12	0.3	1.08	1.9		
Fluoranthene		2.00	1.7	1.62	0.4	1.60	2.8		
Pyrene		1.20	1.0	0.99	0.3	0.90	1.6		
Methyl Pyrene/Fluoranthene		1.37	1.2	0.014	0.004	1.00	1.7		
Benzo(c)phenanthrene	***	0.018	0.02	0.10	0.03	0.11	0.2		
Chrysene/Benz(a)anthracene	*	0.013	0.01	0.28	0.08	1.00	1.7		
Methyl chrysenes	*	0.64	0.06	0.082	0.02	0.62	1.1		
7,12-Dimethylbenz(a)anthracene	****	--	--	--	--	--	--		
Benzo fluoranthenes	**	0.38	0.3	0.14	0.04	2.50	4.3		
Benz(a and e)pyrenes	***	0.26	0.2	0.061	0.02	2.21	3.8		
Perylene		--	--	--	--	--	--		
3-Methylcholanthrene	****	0.16	0.1	0.033	0.009	1.53	2.7		
Indeno(1,2,3,-cd)pyrene	*	0.13	0.1	0.007	0.002	1.20	2.1		
Benzo(ghi)perylene		0.07	0.06	0.009	0.002	1.22	2.1		
Dibenzo(a,h)anthracene	***	0.24	0.2	--	--	--	--		
Dibenzo(c,g)carbazole	***	--	--	--	--	--	--		
Dibenz(ai and ah)pyrenes	***	0.08	0.07	--	--	1.08	1.9		
POM		8.7		6.7		16.5			
POM Loading			7.6		1.8		28.7		

TABLE 4. (Continued)

Component	NAS Notation	Run No. 4 Time Segment: 1 mg	1 mg/Nm^3	2 mg	2 mg/Nm^3	3 mg	3 mg/Nm^3	4 mg	4 mg/Nm^3
Anthracene/Phenanthrene		0.035	0.05	0.010	0.006	0.017	0.02	0.041	0.1
Methyl anthracenes		0.020	0.03	0.020	0.01	0.011	0.01	0.024	0.08
Fluoranthene		0.035	0.05	0.035	0.02	0.011	0.01	0.018	0.06
Pyrene		0.030	0.04	0.030	0.02	0.010	0.01	0.018	0.06
Methyl Pyrene/Fluoranthene		0.020	0.03	0.005	0.003	0.003	0.003	0.019	0.07
Benzo(c)phenanthrene	***	0.005	0.007	0.015	0.01	0.001	0.001	0.003	0.01
Chrysene/Benz(a)anthracene	*	0.040	0.06	0.010	0.006	0.012	0.01	0.015	0.05
Methyl chrysenes	*	0.020	0.03	0.005	0.003	0.005	0.005	0.013	0.05
7,12-Dimethylbenz(a)anthracene	****	—	—	—	—	—	—	—	—
Benzo fluoranthenes	**	0.015	0.02	0.010	0.006	0.010	0.01	0.008	0.03
Benz(a and e)pyrenes	***	0.010	0.01	0.010	0.006	0.009	0.009	0.012	0.04
Perylene		—	—	—	—	—	—	—	—
3-Methylcholanthrene	****	0.005	0.007	0.005	0.003	0.001	0.001	0.013	0.05
Indeno(1,2,3,-cd)pyrene	*	0.005	0.007	0.010	0.006	—	—	0.004	0.01
Benzo(ghi)perylene		0.003	0.004	0.003	0.002	—	—	0.003	0.01
Dibenzo(a,h)anthracene	***	—	—	—	—	—	—	—	—
Dibenzo(c,g)carbazole	***	—	—	—	—	—	—	—	—
Dibenz(ai and ah)pyrenes	***	—	—	—	—	—	—	—	—
POM		0.24		0.17		0.090		0.19	
POM Loading			0.33		0.11		0.09		0.66

TABLE 4. (Continued)

Component	RAS Notation	Run No. 5 Time Segment: 1 mg	1 mg/Nm^3	2 mg	2 mg/Nm^3	3 mg	3 mg/Nm^3	4 mg	4 mg/Nm^3
Anthracene/Phenanthrene		0.32	0.6	0.48	0.4	0.45	0.6	0.37	0.2
Methyl anthracenes		0.23	0.4	0.41	0.3	0.019	0.02	0.40	0.2
Fluoranthene		0.054	0.09	0.19	0.1	0.013	0.02	0.076	0.03
Pyrene		0.049	0.08	0.17	0.1	0.098	0.1	0.12	0.05
Methyl Pyrene/Fluoranthene		0.061	0.1	0.11	0.06	0.090	0.1	0.24	0.1
Benzo(c)phenanthrene	***	0.004	0.007	0.017	0.003	0.008	0.01	0.15	0.06
Chrysene/Benz(a)anthracene	*	0.033	0.06	0.10	0.02	0.073	0.09	0.066	0.03
Methyl chrysenes	*	0.033	0.06	0.031	0.02	0.043	0.05	0.062	0.03
7,12-Dimethylbenz(a)anthracene	****	—	—	—	—	—	—	—	—
Benzo fluoranthenes	**	0.017	0.03	0.019	0.01	0.051	0.06	0.33	0.1
Benz(a and e)pyrenes	***	0.023	0.04	0.009	0.007	0.041	0.05	0.62	0.3
Perylene		—	—	—	—	—	—	—	—
3-Methylcholanthrene	****	0.013	0.02	—	—	0.032	0.04	0.51	0.2
Indeno(1,2,3,-cd)pyrene	*	0.004	0.007	0.001	0.0007	0.023	0.03	0.19	0.08
Benzo(ghi)perylene		0.003	0.005	0.001	0.0007	0.014	0.02	0.12	0.05
Dibenzo(a,h)anthracene	***	0.007	0.01	—	—	—	—	0.15	0.06
Dibenzo(c,g)carbazole	***	—	—	—	—	—	—	—	—
Dibenz(ai and ah)pyrenes	***	—	—	—	—	0.019	0.02	0.066	0.03
POM		0.87		1.5		1.3		3.5	
POM Loading			1.5		1.1		1.6		1.5

TABLE 4. (Continued)

Component	NAS Notation	Run No. 6 Time Segment: 1 mg	1 mg/Nm^3	2 mg	2 mg/Nm^3	3 mg	3 mg/Nm^3	4 mg	4 mg/Nm^3
Anthracene/Phenanthrene		0.085	0.1	0.46	0.3	3.48	0.3	1.31	0.2
Methyl anthracenes		0.044	0.06	0.44	0.3	1.12	0.1	0.91	0.2
Fluoranthene		0.020	0.03	0.24	0.2	1.15	0.1	0.27	0.05
Pyrene		0.013	0.02	0.17	0.1	0.70	0.07	0.19	0.04
Methyl Pyrene/Fluoranthene		0.019	0.03	0.16	0.1	1.09	0.1	0.86	0.2
Benzo(c)phenanthrene	***	0.0002	0.0003	0.017	0.01	0.32	0.03	0.39	0.07
Chrysene/Benz(a)anthracene	*	0.090	0.1	0.011	0.007	0.36	0.03	1.68	0.3
Methyl chrysenes	*	0.042	0.06	0.045	0.03	1.75	0.02	1.22	0.2
7,12-Dimethylbenz(a)anthracene	****	--	--	--	--	--	--	--	--
Benzo fluoranthenes	**	0.025	0.04	0.039	0.02	1.37	0.1	0.40	0.08
Benz(a and e)pyrenes	***	0.015	0.02	0.018	0.01	1.10	0.1	0.47	0.09
Perylene		--	--	--	--	--	--	--	--
3-Methylcholanthrene	****	0.026	0.04	0.010	0.006	1.03	0.1	0.12	0.23
Indeno(1,2,3,-cd)pyrene	*	0.007	0.01	0.007	0.004	--	--	--	--
Benzo(ghi)perylene		0.005	0.007	0.006	0.004	--	--	--	--
Dibenzo(a,h)anthracene	***	--	--	0.018	0.01	--	--	--	--
Dibenzo(c,g)carbazole	***	--	--	--	--	--	--	--	--
Dibenz(ai and ah)pyrenes	***	--	--	--	--	--	--	--	--
POM		0.39		1.75		16.7		7.82	
POM Loading			0.57		1.1		1.6		1.5

TABLE 4. (Continued)

Component	NAS Notation	Run No.9 Time Segment: 1 mg	1 mg/Nm^3	2 mg	2 mg/Nm^3	3 mg	3 mg/Nm^3	4 mg	4 mg/Nm^3
Anthracene/Phenanthrene		0.022	0.07	0.010	0.01	0.0043	0.005	0.0082	0.003
Methyl anthracenes		0.039	0.1	0.0055	0.05	0.0015	0.002	0.0030	0.001
Fluoranthene		0.0033	0.01	0.014	0.01	0.0014	0.002	0.0021	0.0008
Pyrene		0.0036	0.01	0.014	0.01	0.00060	0.0007	0.0011	0.0004
Methyl Pyrene/Fluoranthene		0.0056	0.02	0.014	0.01	0.00070	0.0008	0.0016	0.0006
Benzo(c)phenanthrene	***	0.0018	0.005	0.0074	0.007	0.00035	0.0004	0.00085	0.0003
Chrysene/Benz(a)anthracene	*	0.0088	0.03	0.035	0.03	0.0024	0.0003	0.0034	0.001
Methyl chrysenes	*	0.0034	0.01	0.012	0.01	0.0015	0.002	0.0025	0.001
7,12-Dimethylbenz(a)anthracene	****	—	—	—	—	—	—	—	—
Benzo fluoranthenes	**	0.010	0.03	0.031	0.03	0.0038	0.004	0.0042	0.002
Benz(a and e)pyrenes	***	0.0083	0.03	0.0097	0.09	0.0014	0.002	0.0021	0.0008
Perylene									
Methylbenzopyrenes	****	0.0051	0.02	0.0045	0.004	0.0014	0.002	0.0010	0.0004
Indeno(1,2,3,-cd)pyrene	*	—	—	—	—	0.00040	0.0005	—	—
Benzo(ghi)perylene		—	—	—	—	0.00030	0.0004	—	—
Dibenzo(a,h)anthracene	***	—	—	—	—	—	—	—	—
Dibenzo(c,g)carbazole	***	—	—	—	—	—	—	—	—
Dibenz(ai and ah)pyrenes	***	—	—	—	—	—	—	—	—
POM		0.11		0.16		0.020		0.30	
POM Loading			0.35		0.15		0.022		0.012

TABLE 4. (Continued)

Component	NAS Notation	Run No. 10 Time Segment: 1 mg	1 mg/Nm^3	2 mg	2 mg/Nm^3	3 mg	3 mg/Nm^3	4 mg	4 mg/Nm^3
Anthracene/Phenanthrene		0.0037	0.009	0.0067	0.002	0.014	0.01		
Methyl anthracenes		0.0018	0.004	0.0022	0.0005	0.030	0.03		
Fluoranthene		0.0052	0.01	0.0035	0.0008	0.0036	0.004		
Pyrene		0.0053	0.01	0.00095	0.0002	0.0034	0.003		
Methyl Pyrene/Fluoranthene		0.0053	0.01	0.0010	0.0002	0.0070	0.007		
Benzo(c)phenanthrene	***	0.0030	0.008	0.00090	0.0002	0.0021	0.002		
Chrysene/Benz(a)anthracene	*	0.013	0.03	0.0040	0.001	0.011	0.01		
Methyl chrysenes	*	0.0040	0.01	0.0029	0.007	0.0078	0.008		
7,12-Dimethylbenz(a)anthracene	****	--	--	--	--	--	--		
Benzo fluoranthenes	**	0.010	0.02	0.0074	0.002	0.015	0.02		
Benz(a and e)pyrenes	***	0.0032	0.008	0.0023	0.006	0.0052	0.005		
Perylene		--	--	--	--	--	--		
Methylbenzopyrenes	****	0.0015	0.004	0.0014	0.0003	0.0048	0.005		
Indeno(1,2,3,-cd)pyrene	*	--	--	--	--	0.0017	0.002		
Benzo(ghi)perylene		--	--	--	--	0.00060	0.0006		
Dibenzo(a,h)anthracene	***	--	--	--	--	--	--		
Dibenzo(c,g)carbazole	***	--	--	--	--	--	--		
Dibenz(ai and ah)pyrenes	***	--	--	--	--	--	--		
POM		0.056		0.033		0.11			
POM Loading			0.14		0.008		0.11		

TABLE 4. (Continued)

Component	NAS Notation	Run No. 11 Time Segment: 1&2 mg	Run No. 11 Time Segment: 1&2 mg/Nm^3	Run No. 11 Time Segment: 3&4 mg	Run No. 11 Time Segment: 3&4 mg/Nm^3	Run No. 12 1&2 mg	Run No. 12 1&2 mg/Nm^3	Run No. 12 3&4 mg	Run No. 12 3&4 mg/Nm^3
Anthracene/Phenanthrene		0.41	0.2	0.26	0.08	0.23	0.14	0.28	0.09
Methyl anthracenes		0.28	0.2	0.26	0.08	0.096	0.06	0.10	0.03
Fluoranthene		0.10	0.06	0.047	0.01	0.14	0.09	0.11	0.04
Pyrene		0.057	0.03	0.069	0.02	0.81	0.5	0.068	0.02
Methyl Pyrene/Fluoranthene		0.022	0.01	0.013	0.004	0.051	0.03	0.081	0.03
Benzo(c)phenanthrene	***	0.014	0.008	0.0089	0.003	0.065	0.04	0.062	0.02
Chrysene/Benz(a)anthracene	*	0.030	0.02	0.016	0.005	0.047	0.03	0.10	0.03
Methyl chrysenes	*	0.0061	0.003	0.011	0.004	0.016	0.01	0.052	0.02
7,12-Dimethylbenz(a)anthracene	****	—	—	—	—	—	—	—	—
Benzo fluoranthenes	**	—	—	—	—	0.058	0.04	0.045	0.01
Benz(a and e)pyrenes	***	—	—	—	—	0.031	0.02	0.027	0.009
Perylene		—	—	—	—	0.012	0.008	0.019	0.006
Methylbenzopyrenes	****	—	—	—	—	0.016	0.01	0.021	0.007
Indeno(1,2,3,-cd)pyrene	*	—	—	—	—	0.015	0.009	0.017	0.006
Benzo(ghi)perylene		—	—	—	—	0.0071	0.004	0.014	0.005
Dibenzo(a,h)anthracene	***								
Dibenzo(c,g)carbazole	***								
Dibenz(ai and ah)pyrenes	***								
POM		0.92		0.69		1.6		1.0	
POM Loading			0.53		0.22		0.81		0.33

TABLE 4. (Continued)

Component	NAS Notation	Run No. 13 Time Segment: 1&2 mg	Run No. 13 Time Segment: 1&2 mg/Nm^3	Run No. 13 Time Segment: 3&4 mg	Run No. 13 Time Segment: 3&4 mg/Nm^3	Run No. 14 1&2 mg	Run No. 14 1&2 mg/Nm^3	Run No. 14 3&4 mg	Run No. 14 3&4 mg/Nm^3
Anthracene/Phenanthrene		0.096	0.05	0.11	0.03	0.24	0.1	0.082	0.02
Methyl anthracenes		0.041	0.02	0.051	0.02	0.13	0.08	0.0057	0.02
Fluoranthene		0.037	0.02	0.030	0.009	0.10	0.06	0.018	0.005
Pyrene		0.017	0.01	0.024	0.008	0.062	0.04	0.018	0.005
Methyl Pyrene/Fluoranthene		0.013	0.007	0.028	0.009	0.042	0.02	0.034	0.01
Benzo(c)phenanthrene	***	0.069	0.04	0.097	0.03	0.020	0.01	0.025	0.008
Chrysene/Benz(a)anthracene	*	0.026	0.01	0.048	0.02	0.045	0.03	0.090	0.03
Methyl chrysenes	*	0.013	0.007	0.018	0.006	0.023	0.01	0.11	0.003
7,12-Dimethylbenz(a)anthracene	****	—	—	—	—	—	—	—	—
Benzo fluoranthenes	**	0.058	0.03	0.058	0.02	0.037	0.02	0.035	0.01
Benz(a and e)pyrenes	***	0.030	0.02	0.034	0.01	0.018	0.01	0.025	0.008
Perylene		0.0095	0.005	0.010	0.003	0.0068	0.04	0.0081	0.002
Methylbenzopyrenes	****	0.022	0.01	0.036	0.01	0.022	0.01	0.039	0.01
Indeno(1,2,3,-cd)pyrene	*	0.013	0.007	0.014	0.004	0.0046	0.003	0.0096	0.003
Benzo(ghi)perylene		0.0077	0.004	0.0072	0.002	0.0023	0.001	0.0077	0.002
Dibenzo(a,h)anthracene	***	—	—	—	—	—	—	—	—
Dibenzo(c,g)carbazole	***	—	—	—	—	—	—	—	—
Dibenz(ai and ah)pyrenes	***	—	—	—	—	—	—	—	—
POM		0.46		0.57		0.74		0.56	
POM Loading			0.26		0.18		0.44		0.17

TABLE 4. (Continued)

Component	NAS Notation	Run No. 15 Time Segment: 1&2 mg	Run No. 15 Time Segment: 1&2 mg/Nm^3	Run No. 15 Time Segment: 3&4 mg	Run No. 15 Time Segment: 3&4 mg/Nm^3	Run No. 16 1&2 mg	Run No. 16 1&2 mg/Nm^3	Run No. 16 3&4 mg	Run No. 16 3&4 mg/Nm^3
Anthracene/Phenanthrene		0.024	0.01	0.64	0.2	0.67	0.3	0.42	0.1
Methyl anthracenes		0.014	0.008	0.39	0.1	0.44	0.2	0.29	0.08
Fluoranthene		0.052	0.03	0.22	0.05	0.44	0.2	0.12	0.03
Pyrene		0.040	0.02	0.16	0.04	0.29	0.1	0.13	0.04
Methyl Pyrene/Fluoranthene		0.045	0.03	0.27	0.07	0.33	0.1	0.27	0.08
Benzo(c)phenanthrene	***	0.047	0.03	0.079	0.02	0.18	0.07	0.49	0.1
Chrysene/Benz(a)anthracene	*	0.042	0.02	0.40	0.1	0.14	0.05	0.29	0.08
Methyl chrysenes	*	0.019	0.01	0.26	0.06	0.073	0.03	0.26	0.08
7,12-Dimethylbenz(a)anthracene	****	--	--	--	--	--	--	--	--
Benzo fluoranthenes	**	0.046	0.03	0.026	0.06	0.048	0.02	0.028	0.08
Benz(a and e)pyrenes	***	0.028	0.02	0.017	0.04	0.028	0.01	0.022	0.06
Perylene		0.0019	0.01	0.012	0.03	0.017	0.007	0.026	0.08
Methylbenzopyrenes	****	0.020	0.01	0.027	0.07	0.037	0.01	0.042	0.01
Indeno(1,2,3,-cd)pyrene	*	0.0078	0.004	0.0091	0.02	0.0056	0.002	0.0072	0.002
Benzo(ghi)perylene		0.0063	0.004	0.0058	0.01	0.0066	0.003	0.0056	0.002
Dibenzo(a,h)anthracene	***	--	--	--	--	--	--	--	--
Dibenzo(c,g)carbazole	***	--	--	--	--	--	--	--	--
Dibenz(ai and ah)pyrenes	***	--	--	--	--	--	--	--	--
POM		0.41		2.5		2.5		2.0	
POM Loading			0.23		0.60		0.98		0.58

TABLE 4. (Continued)

TABLE 4. (Continued)

Component	NAS Notation	Run No. 17 Time Segment: 1 &2 mg	1 &2 mg/Nm^3	3&4 mg	3&4 mg/Nm^3	3 mg	3 mg/Nm^3	4 mg	4 mg/Nm^3
Anthracene/Phenanthrene		0.99	0.6	0.92	0.5				
Methyl anthracenes		0.35	0.2	0.78	0.4				
Fluoranthene		0.12	0.07	0.37	0.2				
Pyrene		0.22	0.1	0.27	0.2				
Methyl Pyrene/Fluoranthene		0.63	0.4	0.55	0.3				
Benzo(c)phenanthrene	***	0.077	0.04	0.081	0.05				
Chrysene/Benz(a)anthracene	*	0.37	0.2	0.067	0.04				
Methyl chrysenes	*	0.14	0.08	0.065	0.04				
7,12-Dimethylbenz(a)anthracene	****	--	--	--	--				
Benzo fluoranthenes	**	0.025	0.01	0.068	0.04				
Benz(a and e)pyrenes	***	0.010	0.006	0.044	0.03				
Perylene		0.016	0.009	0.015	0.009				
Methylbenzopyrenes	****	0.014	0.008	0.018	0.01				
Indeno(1,2,3,-cd)pyrene	*	0.0034	0.002	0.0055	0.003				
Benzo(ghi)perylene		0.0021	0.001	0.0032	0.002				
Dibenzo(a,h)anthracene	***	--	--	--	--				
Dibenzo(c,g)carbazole	***	--	--	--	--				
Dibenz(ai and ah)pyrenes	***	--	--	--	--				
POM		3.0		3.3					
POM Loading			1.7		1.9				

COAL COMBUSTION ON THE FUEL BED

The fuel bed was observed (through the stoker firedoor) for brief periods of time throughout each of the runs listed in Table 2. It was observed that for all coals except anthracite, the fuel bed and the resulting flame and flow patterns were continuously changing during the runs. Accordingly, it is anticipated that emission levels would also vary to some degree throughout each run and from one run to another (as for Run 1 and replicate Runs 2 and 8 of Table 3). Emissions data were collected over 4 to 6 cycles of operation which tended to lessen the effect of these variations, thus, "average" emission levels were determined. Some general observations are discussed below for each of the coals.

High Volatile Bituminous Coal

In general, this coal tended to cake, creating a nonuniform air distribution through the bed. The 20-minutes-on/40-minutes-off cycle did not allow the fuel bed to become sufficiently hot to burn out the tars. These tars became plastic and cemented pieces of coal together, forming cakes of various sizes that retarded the even distribution of air through the fuel bed. The caking was less severe during the 50-minutes-on/10-minutes-off cycle of Run 3. However, during Run 3 it was observed that once the bed began to cake, the burning rate became extremely variable. During the initial "on" period (Time Segment 1), coal fed into the retort would not burn uniformly and completely as there was a deficiency of air. As the bed became hotter during the latter part of Time Segment 2, this unburned coal (as well as the coal being fed into the retort) would ignite, resulting in an increase in the burning rate. This observation was verified by the fact that excess oxygen level of the flue gases was varying for a constant combustion air flow rate.

An important aspect of the high-volatile bituminous coal runs are the relatively high particulate and POM loadings during the off period (Time Segments 3 and 4). Smoke was visible from the stack only during this period (except during the last two cycles of Run 1 in which the fuel bed degraded noticeably) and was most noticeable (about a Ringelmann 1) during the 5-minute period after stoker shutdown (Time Segment 3). During the off-period (Time Segments 3 and 4), the CO levels were greater than 1250 ppm; they were less than 500 ppm during the on-period. It is conjectured that the high particulate and POM loadings during the off-period are attributed to the incomplete combustion of tars emitted from this volatile coal. This can be further evidenced by the plugging (apparently by condensible tars) of the filter during Time Segment 4 of the first cycle in both Runs 1 and 2

Low Volatile Bituminous Coal

The low volatile bituminous coal fired in Run 6 has high caking properties. This coal tended to cake into large masses that interfered with the overfire air. Because of its relatively low volatile content, this bituminous coal could be considered a natural smokeless as Bacharach smoke levels of approximately 4 and 9 were measured during the on- and off-periods,

respectively. The excess air levels varied considerably during this run, indicating a varying burning rate and nonuniform fuel bed.

Processed "Smokeless" Coal

This lignite char was soft and broke into fines as it was conveyed by the feed screw to the retort. As a consequence, there was an excessive amount of fines burning as sparklers above the bed. In addition, the coal fines appeared to mat the fuel bed somewhat. It is conjectured that these coal fines contributed significantly to the particulate loadings in Time Segments 1 and 2 of Run 4. Particulate loadings were low during the off-period although CO levels were greater than 1250 ppm. This process coal was truly "smokeless" as it was fired smokelessly without overfire air.

Western Subbituminous Coal

This coal had a slight tendency to cake forming small, but visible, blowholes in the fuel bed. Although overfire air was required to achieve smokeless operation, Bacharach smoke levels less than 2 were measured during portions of the "on" cycle. Bacharach smoke numbers greater than 9 were measured during the off-period, although no visible smoke could be detected from the stack. (These spots had a yellowish tint, however, and it was difficult to visually determine the Bacharach smoke number.)

Anthracite

Unlike the other coals, the anthracite did not cake nor did the ash fuse into a clinker. As a consequence, the fuel-bed conditions remained stable for over 24 cycles of operation. The anthracite coal was noticeably more difficult to ignite than any of the other coals. However, once ignited, this fuel bed burned uniformly with a blue flame. Overfire air was not used yet Bacharach smoke numbers were less than 1. It is anticipated that the use of overfire air could have reduced CO levels.

FACTORS INFLUENCING EMISSION LEVELS

In general, the particulate, POM, and smoke emission levels appear consistent in that the higher particulate levels correspond to higher POM and smoke levels. The exception is the particulate level of the processed lignite char; however, the relatively high particulate loading obtained with this coal is attributed to the excessively large amount of fines fed into the fuel bed. The particulate emission levels summarized in Table 5 are within the range of those reported in the literature (7). Likewise, SO_2 and NO emission levels are within the range of those reported. Although there are no POM emission data from stokers in the literature (utilizing the sampling and analytical techniques of this research), it is observed that levels of POM generated from steady-state firing of the stoker are significantly higher (at least several orders of magnitude) than those generated from steady-state operation of oil-fired equipment (8). Previously, POM data were reported as benz(a)pyrene (9), only one of the approximately 18 species that are currently scanned for during analysis. In addition, some of the POM emission levels that have been reported in the literature, use

TABLE 5. THE EFFECT OF VOLATILE MATTER AND FREE SWELLING INDEX ON PARTICULATE AND POM EMISSIONS FROM COAL COMBUSTION DURING A 20-MINUTE-ON/40-MINUTE-OFF CYCLE AND CONTINUOUS FIRING RATES OF 45 TO 67 LB/HR (20 TO 30 Kg/hr)

Run	Coal	Volatile Matter	Free Swelling Index	Particulate Emissions, g/lb[a] coal fed	POM Emissions, mg/lb[a] coal fed	Bacharach Smoke "on" Cycle
1	High volatile bituminous	40	5	3.9	86	9
2	High volatile bituminous	40	5	4.1	82	>9
6	Low volatile bituminous	21	7-1/2	1.4	27	4
5	Western subbituminous	37	1/2	0.50	10	3
7	Western subbituminous	37	1/2	0.43	--	5
4	Processed lignite char	16	0	3.2	1.8	4
9	Anthracite	4	0	0.33	0.86	1/2

(a) 1 g/lb = .454 g/Kg and 1 mg/lb = .454 ng/Kg.

the BaP emission as a key to which a constant factor is applied to predict total POM levels. The data contained in Table 4 indicate this method of predicting total POM is somewhat questionable, as the ratio of the BaP emission to the total POM emissions varies considerably.

Because of the inherent scatter of stoker-coal combustion data, the complex interrelation among the factors that affect coal combustion, the limited amount of data, specific correlations and/or quantitative relations could not be identified that could be substantiated by the data. However, the data suggest that certain coal properties and stoker operating factors do influence emissions.

Coal Properties

Particulate and POM emission levels are related to the chemical and physical properties of the coal that affect the combustion processes of these coals. As an example, particulate can consist of unburned carbon (which related to volatile content of the coal). fly ash (which relates to ash content and coal size), and condensible tars (which relates to volatile content).

Volatile Content--

As indicated in Tables 1 and 2, coals with the higher volatile content generally produced higher levels of particulate and POM. These higher emission loadings are attributed to the incomplete combustion of the tars emitted from the coal. This can be further evidenced by the relatively high emission loadings for the off cycle, where conditions inhibit the burnout of tar (low-bed temperature and insufficient supply of air to the fuel bed). The differences in the particulate loadings of each of the coals were considerably less during the "on" cycle than in the "off" cycle.

Free-Swelling Index--

The free-swelling index is a measure of the caking property of the coal. The fuel bed of a caking coal generally degrades over a period of time as large fissures form in the bed, separating masses of coke of various sizes and preventing the even distribution of air through the fuel bed. Thus, the coals with the highest free-swelling index had the highest particulate and POM emissions levels.

Coal Size--

Some undersize fines [less than 1/4 in. (6.4 mm)] are unavoidably formed during crushing, screening, and feeding of coal. Less than 15 percent fines is acceptable (and may be beneficial in uniform feeding) while greater than this amount interferes with uniform air distribution. In addition, an excessive amount of fines can result in coal particles being lifted from the bed. Although these coal particles burn, the remaining ash is emitted to the stack. Run 4 is an example of this as a significant amount of coal fines were burned above the bed resulting in a relatively high particulate loading during the "on" cycle. It is thought that this high particulate loading was attributed to fly ash rather than resulting from incomplete combustion of the coal as suggested by the relatively low POM loading during the "on" cycle.

Ash Content--

The ash content has secondary effects in generating particulate emission. A substantial portion of the ash should remain in the fuel bed. However, the properties of this ash can be important in the overall performance of the stokers. For example, a low-ash fusion coal could create clinkers that interfere with the uniform feed of coal and distribution of air. From Tables 1 and 7 it is noted that the coals with the lowest ash content generated the highest particulate loading, thus suggesting that other factors (rather than ash content) are the concomitant indicators in predicting particulate loading from stoker combustion.

Certain properties of the ash may also have an effect on other emissions. For instance, the relatively high lime content of ash in some of the Western coals can react with the sulfur and, thus, reduce the conversion of fuel sulfur to sulfur oxides. However, a complete coal and particulate analysis is required to verify the extent of the effect of ash content on both gaseous and solid emissions.

Effect of Firing Rate

Both the high volatile bituminous and the Western subbituminous were fired at rates corresponding to low-, mid-, and full-boiler capacities. For the Western coal, it appears that firing rate has no significant effect on particulate and POM emissions. For the high volatile coal, there appears to be no appreciable differences among the particulate loadings during the "on" cycle for the 3 firing rates. However, the unexpectedly lower POM loadings and particulate loadings during the "off" cycle ofRuns 12 and 13, as compared to Runs 1 and 2, are somewhat perplexing. Apparently, the fuel bed condition (a controlling factor during the "off" cycle) of these runs was considerably different. Additional data points are required to verify the results.

Effect of Cycle

From Tables 2 and 3, comparing Runs 1 and 2 with Run 3 for the high volatile coal, and Runs 9 and 10 for anthracite, the duration of the "on" period within a cycle did not have any significant effect on POM and particulate emission. Additional data are needed to determine whether differences in emission levels of these runs are real or are a result of the scatter of the data.

Effect of Overfire Air

Overfire air was necessary to achieve smokeless operation on the coals with volatile matter greater than 20 percent. During the checkout runs, the high volatile bituminous coal was fired with and without overfire air. Particulates were sampled for 60 minutes during steady-state firing. The particulate loadings were nearly identical (being 130 mg/Nm^3 without the overfire air and 140 mg/Nm^3 with the overfire), although the Bacharach smoke levels were 4 with the overfire air and greater than 9 without. Apparently, the smoke contributes a negligible amount to the overall particulate loading. Analysis of the filter from both runs indicated that

approximately half the catch was unburned carbon. Thus, overfire air had an appreciable influence on smoke emission, but had apparently no influence pn particulate emissions.

Effect of the Modified Cycle Operation

During the checkout runs, it was observed that the smoke emissions and the condition of the fuel bed could be controlled by controlling the amount of both the primary and secondary air during the operating cycle. Normally, once set up and adjusted, the residential and small commercial stoker operates at one speed with both the combustion air fan and feed screw operating concurrently. As a result, during the initial "on" period there is an excessive amount of air (Time Segment 1) and during the initial "off" period (both feed screw and fan off) there is a deficiency of air (Time Segment 3). Accordingly, the stoker operation was modified to achieve a better control of air during these periods by (1) during initial "on" period the primary air flow was reduced to 200 lb/hr (91 Kg/hr), approximately 30 to 40 percent of the normal flow rate for the first 5 minutes, and (2) during the initial "off" period the overfire air jets remained on for 5 minutes.

For the high volatile bituminous coals, this modification significantly reduced the POM emissions (by a factor of 7) and reduced to a lesser extent the particulate emissions (by a factor of 2.3) (comparison of Runs 1, 2, and 17). However, for the Western coal, this modification had no significant effect on either the particulate or POM emissions (comparison of Runs 5 and 16). During the normal (not modified) operating cycle, visual observations indicated that combustion in and above the fuel bed was extremely nonuniform for the high volatile bituminous coal and considerably more uniform for the Western. (The particulate and POM emissions measurements confirm this observation.) Visual observation of the fuel bed during operation on the modified cycle indicated that the fuel bed was noticeably more uniform for the high volatile bituminous coal while the modification had no noticeable effect on the fuel bed condition for the Western coal run. Apparently, this type of modification would not improve the burning of good stoker coals (such as the relatively uniform and free-burning Western coal).

OVERVIEW OF EXPERIMENTAL RESULTS

This experimental research demonstrated that smokeless operation of small commercial stokers can be achieved with minor modifications in the stoker design (provision for overfire air) and accurate control of the combustion air. Further, the data indicate that a relatively large amount of particulate and POM emissions are generated during the off-cycle in which there is no control of the air supply. It is possible that emissions can be reduced during this cycle by maintaining a control of the air flow to and above the fuel bed.

From both the analysis of the data and visual observations of the fuel bed, it appears that of the coals evaluated, anthracite is the most

suitable for stoker firing; however, this coal is limited in supply. Similarly, the processed coal appears attractive as a stoker fuel provided it can be manufactured for this type of stoker firing. Also, the Western subbituminous coal is a candidate coal for stokers, provided that minor modifications are included in the design and operation of the stokers and that it can be supplied economically to the Eastern market. The two coals least suited for stoker firing (the high- and low-volatile bituminous) are those with the highest volatile matter content and highest free swelling index. Unfortunately, the supply of these coals is abundant near the largest potential market areas. These coals are more suited to the larger industrial spreader stoker boilers and/or the pulverized coal utility boilers.

SECTION 9

ASSESSMENT OF THE POTENTIAL FOR STOKER COAL UTILIZATION

The assessment of the advisability of increased utilization of coal for residential and small commercial stoker applications includes consideration of boiler-operating efficiency, fuel type and availability, economics, emission assessment, and public acceptance. This assessment is based on the findings of the stoker and processed coal surveys, and the experimental research investigation.

Operating Efficiency

Because of the difficulty in obtaining an accurate energy balance on a small commercial stoker-fired hot water boiler system, a meaningful boiler-operating efficiency could not be determined. A review of the stoker literature also verified that true cyclic efficiency values (not steady state values for continuous firing) are not readily available for stokers or oil/gas fired systems in the size range of interest. However, qualitative comparisons of operating efficiencies (based upon relative differences in excess air levels and stack-gas temperatures) of stokers with those of oil-fired residential systems observed by Barrett, et al (3) suggest that stoker and oil-fired systems operate with about the same overall efficiency (at approximately the same boiler load). Both types of systems operate at excess air levels that approach 100 percent with stack-gas temperature above 500 F (260 C).

It appears that the potential exists to increase efficiency through modifications in burner-boiler designs, but this appears to be more readily achievable in a gas- or oil-fired system. In addition, for coal-fired systems, selection of a coal that minimizes soot deposition on heat transfer surface is necessary to maintain efficiency. For example, the combustion of the high volatile bituminous coal deposited about a 1/8 in. (3.2 mm) layer of soot in the fire tubes after several days of operation, resulting in a stack-gas temperature rise of 100 F (30 C) in that period. On the other hand, the combustion of anthracite deposited only a thin layer (less than 1/32 (0.8 mm) of soot after several days of firing, resulting in a stack-gas temperature rise of about 40 F (22 C).

Efficiency has not been an important consideration in this size of equipment. Although the increasing costs of all fuels makes efficiency a more significant factor in combustion equipment design and operation, it may not be as important a consideration in stoker systems as in oil or gas systems because coal is a relatively more abundant resource than oil or gas.

Fuel Type and Availability

Eventually, our oil and natural gas supplies will be depleted so that alternative methods for residential and small commercial space heating applications will have to be identified. Because residential and commercial installations have been considered high priority users, there appears to be no large curtailment of supply of oil and gas to these users in the immediate future. Where oil and gas have not been available and operating cost is not a major issue, electricity frequently has been used for space heating. The long range supply of energy for space heating is unclear. In twenty years, when our supply of oil and gas may become critical, gasified or liquefied coal, advanced heat pumps, solar energy, and other advanced concepts may be developed to the point that they compete with stokers.

In addition, the fuel type and availability of the coal itself is another consideration. The experimental research indicated the most environmentally suitable coals for stoker firing are those that are low sulfur and free burning (noncaking). However, these properties are not characteristic of coals in abundant supply and/or located near the highest potential market area. (Attempts to minimize the caking tendencies of low-sulfur caking coals, such as those found in West Virginia and Eastern Kentucky within the stoker-boiler system never fully developed (10).) Accordingly, there appears to be a potential market for processed fuel that has low sulfur, low volatile matter, and is free burning.

Economics

In comparison to oil- and gas-fired systems, stoker-fired systems for residential and small commercial space heating applications (less than 1 million Btuh input) are economically unattractive. The stoker itself can cost two to three times more than comparable oil and gas burners (based on a communication with a burner manufacturer). In larger size equipment, this difference is not as great, and in some systems, the capital costs of a stoker may be lower than those of oil and gas burners. In addition, the stoker requires a more elaborate boiler setting, larger floor area, and an area for coal storage--all adding to the installation costs.

Fuel costs must also be considered. These costs vary from region to region and have become difficult to predict. A check on the current fuel prices in Columbus, Ohio, indicates little difference among the energy costs of stoker coal, fuel oil, and natural gas with natural gas being the least expensive. Also with natural gas and fuel oil, there are no costs associated with fuel handling and ash disposal. However, it is anticipated that in the future, costs of natural gas and fuel oil will be increasing at a faster rate than for stoker coal, making stoker firing more economically competitive.

Emission Assessment

Because the emissions from stoker-fired equipment are significantly higher than those from oil- or gas-fired equipment, an increase in utilization of coal for residential and small commercial space heating equipment will have a significant impact on the environment. Stokers emit pollutants at low atmospheric levels and, thus, the pollutants are not easily dispersed. In addition, residential and small commercial stoker installations would be concentrated in high population density areas, further adding to the dispersion problem. It is anticipated that in addition to using low sulfur coals, stoker-boiler systems should be required to include a mechanical collector on the stack to control particulate emissions. Alternatively, utilizing electricity rather than oil or gas would lower (slightly) the emissions around the site of the installation, but the emissions from the new power plants would have to be considered. However, these emissions could be more economically controlled.

The increased utilization of stoker coal creates additional emissions associated with delivery of the coal and the removal of the ash that are not present in gas- and oil-fired systems. A negligible increase in vehicular emissions would be anticipated in regard to this aspect.

Public Acceptance

Stoker firing for space heating would not be acceptable to the American public unless there were no other alternatives available or these alternatives were economically unattractive. They are accustomed to the convenience, dependability, and cleanliness of utilizing oil and gas. Factors that contribute to the unattractiveness of stoker firing include:

- Storage area required
- Ash disposal problems
- Uncleanliness
- Environmentally unattractive
- Increased maintenance
- Overheating of residence during some periods of early fall and late spring. (The fuel bed serves as a pilot and must be kept alive by operating the stoker even though heat is not required.)
- Larger temperature excursions. [It is not practical to operate stokers with short "on" times of 4 to 5 minutes, as some oil- and gas-fired burners operate (3)].

However, it must be remembered that the majority of residential and small commercial space heating equipment was coal-fired as late as 25 years ago. It was accepted then and will be accepted again if no viable alternative can be identified.

General Overview

In summary, the current economic and environmental factors associated with stoker firing are unfavorable for increased utilization of coal in residential and small commercial space heating applications. Although our supplies of fuel oil and natural gas are dwindling, there appears to be no immediate or near term shortage for the vast majority of small users. Where shortages exist, electric space heating coupled with extensive insulation, rather than stoker firing, will be selected as the alternative.

In the event that there is an increase in the utilization of stokers, stoker designs need to be modified and processed coals need to be made more marketable as current designs and the fuels that are most readily available would not be attractive from the operational and environmental viewpoints.

APPENDIX A

SURVEY OF STOKER-BOILER MANUFACTURERS

The renewed interest in coal as a fuel for space heating, created by the current shortages in heating oil and natural gas, has even penetrated into the residential and small commercial space heating applications. As late as the 1950's coal was still used as a major fuel for these applications but, thereafter, was rapidly displaced by gas and oil. With the decline in coal use, there was an accompanying decline in the number of stoker and boiler manufacturers until only one major manufacturer and only a few boiler manufacturers remained. However, the recent oil embargo has renewed interest in these stoker-boiler systems.

OBJECTIVES

The objectives of this stoker survey were

- To identify the stoker-boiler systems most commonly used in the 5 - 20 x 10^4 Btuh (52 - 210 MJ/hr) range
- To identify the stoker-boiler systems most commonly used in the 2 - 10 x 10^5 Btuh (210 - 1050 MJ/hr) range
- To identify the types of fuels that stoker-boiler systems are capable of burning
- To identify the types of heating systems commonly used with stokers
- To assess the potential market area for stoker coal in these size ranges.

In addition, to provide background information, emission factors of stokers and the stoker-boiler population are discussed.

SUMMARY

The findings from the survey of over twenty present or past manufacturers of residential and small commercial stoker-fired space heating equipment (or their representatives) include

- Residential and small commercial stoker-boilers are similar in design as systems components are scaled (up or down) to match the desired range of operation. The stokers are of the underfeed type.
- The conventional underfeed bituminous stokers are capable of firing most coals except anthracite.
- The conventional underfeed anthracite stokers are designed to fire anthracite only. There is a possibility that this stoker could fire "smokeless" or processed coal if properly sized.
- There is only one manufacturer of the conventional anthracite stoker and only one manufacturer of the conventional bituminous stoker in the size ranges of interest. One additional manufacturer makes an anthracite stoker that is an integral part of the boiler system.
- There are only three major manufacturers (H. B. Smith, Kewanee, and Weil McLain) of boilers suitable for stoker firing. Of these, only Weil McLain currently manufacturers a boiler in the residential size range.
- There are over 200,000 living units heated by anthracite.
- There has been renewed interest in stoker firing in the size ranges of interest. The majority of activity has been for small commercial applications rather than residential.
- The majority of the new stoker-boiler systems are designed for hot water, while most replacements are for steam systems. There has been some renewed interest in residential stoker-fired warm air furnaces.

EMISSION FACTORS

Table 6 summarizes the emission factors of residential and small commercial fossil-fuel combustion equipment for space heating application (11). As noted, the particulate and sulfur dioxide emissions are significantly higher for coal combustion than for distillate fuel oil or natural gas combustion, especially considering that coal can have an ash content as high as 20 percent and a sulfur content as high as 4 percent.

To minimize emissions from coal-fired equipment in this size range necessitates the utilization of a low-sulfur, low-ash coal. Whereas fuel oil can be desulfurized before firing, there are no commercial viable methods for treating or preparing coal (other than washing) to reduce emissions of SO_2. For particulate control, it is conceivable that a mechanical collector could be utilized in the stack to collect a substantial amount of particulate.

Although Table 6 does not include smoke emission, smoke levels from stokers can be high (visible smoke from the stack) especially for the few minutes after stopping the stoker. This smoke problem can be minimized by modification of the stoker-boiler system to provide a better control of the combustion air.

POPULATION OF SPACE-HEATING EQUIPMENT

Residential Equipment

Table 7 lists an estimate of (1) the sales, and (2) the number of units in operation of all automatic space-heating equipment in the residential size range from 1941 through 1969 (12). As noted, stoker sales have been decreasing since 1946 and recently have accounted for less than 1 percent of sales. Likewise, the number of stokers in operation has been continually declining. (These numbers are for automatic heating equipment and do not reflect the number of hand-fired coal units still in operation.) About 23 percent of these automatic space-heating units are utilized in steam or hot water systems (13).

TABLE 6. EMISSION FACTORS FOR FOSSIL FUEL COMBUSTION (11)

	Particulates lb/10^6 Btu	Sulfur Oxides lb/10^6 Btu	Carbon Monoxide lb/10^6 Btu	Hydrocarbons lb/10^6 Btu	Nitrogen Oxides lb/10^6 Btu
Coal - Bituminous					
Stoker	0.08	1.525	0.40	0.12	0.14
Hand-fired	0.8	1.525	3.6	0.80	0.07
- Anthracite					
Hand-fired	0.4	1.525	3.6	0.10	0.07
Distillate oil	0.007	0.955	0.031	0.02	0.08
Natural gas	0.019	0.0006	0.020	0.008	0.08 to 0.120

TABLE 7. AUTOMATIC HEATING TRENDS

	ANNUAL SALES					OPERATING AT END OF YEAR				
		% of total					% of total			
	Total	Stoker	Oil-burners	Gas-burners	Electric	Total	Stoker	Oil-burners	Gas-burners	Electric
1941	652,391	28.0%	51.1%	20.9%		4,514,627	17.8%	53.2%	29.0%	
1942	225,041	35.1	44.2	20.6		4,615,785	19.0	51.7	29.3	
1943	64,465	27.5	51.9	20.6		4,633,755	19.3	51.3	29.4	
1944	102,028	31.0	48.9	20.1		4,700,130	19.7	50.9	29.4	
1945	321,693	37.1	45.2	17.7		4,979,775	20.7	50.5	28.8	
1946	1,336,316	13.5	37.0	49.5		6,009,347	19.3	47.0	33.7	
1947	1,271,679	4.9	69.8	35.3		7,133,709	16.6	51.2	32.2	
1948	803,222	9.5	56.7	33.8		7,752,498	16.0	51.3	32.7	
1949	1,281,706	2.3	47.9	49.7		8,845,695	14.0	50.8	35.2	
1950	1,210,725	1.1	45,6	53,3		10,434,971	11.3	49.6	39.1	
1951	1,346,794	1.4	50.1	48.5		11,506,701	9.8	49.6	40.6	
1952	1,544,160	1.2	50.4	48.4		12,757,700	8.5	49.7	41.8	
1953	1,636,812	8.0	50.3	48.9		14,085,664	7.1	49.8	43.1	
1954	1,698,459	0.8	43.4	55.7		15,423,130	5.8	49.2	45.0	
1955	1,974,282	0.7	41.0	58.3		17,047,244	4.6	48.5	46.9	
1956	1,809,508	0.8	38.2	60.0		18,542,422	4.0	47.3	48.7	
1957	1,579,088	0.8	36.7	62.7		19,516,099	3.5	46.3	50.2	
1958	1,739,865	0.7	32.7	66.6		20,742,043	2.9	45.0	52.0	
1959	2,061,632	0.7	30.8	64.1		22,697,083	2.4	42.5	52.5	
1960	1,816,962	0.6	26.9	65.5	7.0	23,978,635	2.1	40.9	54.0	3.0
1961	1,936,078	0.5	26.1	63.4	10.0	25,341,538	1.9	39.2	55.3	3.6
1962	2,048,396	0.5	21.1	63.5	14.9	26,166,143	†	38.5	57.5	4.0
1963	2,194,619	0.4	23.7	64.0	13.6	27,393,864	†	37.2	58.2	4.6
1964	2,313,462	0.3	23.8	61.1	14.8	28,691,440	†	36.1	58.5	5.4
1965	2,271,303	0.2	24.0	60.2	15.6	29,779,905	†	35.3	58.2	6.5
1966	2,152,252	†	26.6	59.3	14.1	31,115,265	†	34.4	58.6	7.0
1967*	2,196,853		26.1	63.3	10.6	32,238,332		34.0	58.5	7.5
1968*	2,267,917		27.2	61.3	11.5	33,086,838		33.5	58.6	7.9
1969	2,318,746		25.9	60.7	13.4	33,990,645		32.9	58.8	8.3

* Revised.
† Stoker figures dropped; less than 1% of automatic heating.

Small Commercial

Table 8 estimates the boiler population by number, total design capacity (10^6 Btu/hr), and annual load factor times total design capacity (10^6 Btu/hr) as a function of fuel type for the small commercial size ranges (13). The annual load factor times the total design capacity gives the total fuel consumption. From Table 8 it is noted that stoker boilers comprise about 12 percent of the total number of boilers and comprise about 14 percent of the total fuel consumption in this size range. Nearly all of these boilers are of the fire-tube type and recent sales data indicate about 80 percent are Scotch. It should be noted that in the size ranges up to 5×10^6 Btu/hr, warm air units are making strong inroads into steam and hot water unit sales (13).

STOKER-BOILER SYSTEMS

Table 9 summarizes the currently available stokers. Because anthracite differs in combustion characteristics from bituminous coals, a different stoker design is required to burn this coal successfully. The anthracite and bituminous coal stokers are basically the same except in retort design. The bituminous retort is built to burn efficiently a coal relatively high in volatile matter and to fuse ash into a removable clinker; the anthracite stoker retort, on the other hand, is built to burn efficiently coal of low volatile content and to spill ash into a pit or to the receiver for the ash. Also because anthracite burns with a slow uniform flame, it requires less combustion space than bituminous coals.

Table 10 summarizes the currently available boilers suitable for stoker firing. Cast iron boilers require assembly at the installation site which is an added expense. This type of boiler has the advantage in that it can be installed in existing structures that have limited access to the "boiler room". The steel boilers are packaged boilers that are factory assembled.

Stokers

The Will-Burt Company is currently the only manufacturer of bituminous coal stokers in the size ranges of interest. These stokers are capable of firing most coals except anthracite. Will-Burt's product line includes stokers with capacity ranging from 20 lb/hr to 250 lb/hr. They have been selling about 500 new stokers per year.

The Van Wert Manufacturing Company is currently the only manufacturer of anthracite stokers in the size range of interest. These stokers could possibly fire a process coal if it were suitably sized. Van Wert's product line includes anthracite stokers with capacity ranging from 12 to 100 lb/hr. They have sold only a few units in the past year.

The Axeman-Anderson Company manufacturers an "Anthratube" unit that is an integral stoker-boiler system. The anthracite stoker is designed as

TABLE 8. ESTIMATE OF BOILER POPULATION FOR SMALL COMMERCIAL UNITS (A-3) (a)

Coal Type	Design Capacity, Btu/hr 0.5-1.0x10^6 Commercial	1-2x10^6 Commercial
Stoker coal	4,910	3,387
	4,910	6,774
	1,498	2,066
Pulverized coal	0	109
	0	218
	0	92
Residual oil	5,261	3,496
	5,261	6,992
	1,289	1,713
Distillate oil	19,992	13,547
	19,992	27,094
	4,118	5,581
Nonnatural gas	0	0
	0	0
	0	0
Natural gas	11,644	7,866
	11,644	15,732
	3,703	5,003
Sum	41,807	28,405
	41,807	56,810
	10,608	14,455
Percent stoker	11.7	11.9
	11.7	11.9
	14.1	14.2

(a) Top number in each group is boiler population by number count. Second number is the total design capacity (in 10^6 Btu/hr) of all boilers, that is, the number count times the design capacity of a single unit. The third number is the annual use, that is, the total design capacity of all boilers in the group times the average annual load factor.

TABLE 9. STOKERS

Type	Manufacturer	Capacity lb/hr	Cost,[a] dollars	Characteristic
Conventional bituminous	Will Burt Co.	20 75 100	900 1300 1800	Burns most coals except anthracite
Conventional anthracite	Van Wert Mfg. Company	12 60	511 800	Possibility of burning "smokeless" coal in addition to anthracite
Anthratube	Axeman-Anderson	15 30	1000[b]	Stoker integral part of boiler. Stoker will not mate with other boilers.

(a) Oral quotes as of January 1, 1975. Does not include freight charges.

(b) Also includes boiler.

TABLE 10. BOILERS

Type	Manufacturer	Model	Rating[a] Btu/hr Output	Cost,[b] dollars
Cast-iron	Weil-McLain	K-257	157,000	800
		HK-40-6	1,080,000	3,000
Cast-iron	H. B. Smith		243,000	1,130
			750,000	2,200
Steel tube	Kewanee	3R-1	324,000	2,400
		3R-5	648,000	2,700

(a) Based upon 75 percent efficiency and 12,000 Btu/lb coal.

(b) Oral quotes as of January 1, 1975. Does not include freight charges.

part of the boiler and will not mate with any other boiler. This system also utilizes an induced-draft fan. Axeman-Anderson currently markets boilers in two size ranges, 130,000 Btu/hr and 260,000 Btu/hr, but tandem units can be used for up to 1,000,000 Btu/hr.

Boilers

Only three major manufacturers (Weil McLain, Kewanee, and H. B. Smith) of boilers for stoker firing were identified that have an extensive sales network. Of these only Weil-McLain markets a stoker boiler in the residential size range. Other boiler manufacturers, such as Van Wert and Axeman-Anderson, do market stoker boilers, but their market area is limited to a local region.

RECOMMENDATIONS

From the findings of the survey, it was recommended that both an anthracite (60 lb/hr) and a bituminous (75 lb/hr) stoker be purchased and mated to a Kewanee 3R-5 boiler. It was felt that, because the residential and small commercial stokers were so similar in design, only one boiler size was required to give representative results over the two boiler output ranges of interest. In addition, to obtain satisfactory combustion of anthracite, a stoker specifically designed for anthracite was required.

APPENDIX B

SMOKELESS COAL SURVEY

In comparison to oil and gas, high volatile bituminous coal has been difficult to burn without any visible smoke. Converting this class of coal into a form in which it would not produce visible smoke, no matter how it was fired, was of major importance in the 1930's and 1940's when smoke ordinances were limiting the amount of volatile matter in solid fuels. Now, with the shortage of oil and gas and with the presence of air pollution regulations, there has been a renewed interest in "smokeless" coal.

This survey examines the characteristics, manufacturing methods, and short- and long-term availability of processed smokeless solid fuels and provides background for assessing the suitability of these fuels for use in small stokers.

In addition to the smokeless coal survey, this appendix discusses the selection and acquisition of the other classes of coals used in the experimental investigation.

OBJECTIVES

The major objectives of this survey was to conduct a survey of the manufacturing process for "smokeless" coal. Factors to consider included

- Suitability for stoker-firing
- Environmental impact (both the combustion and manufacturing aspects)
- Analysis
- Long- and short-term availability
- Economics of smokeless coal utilization.

In addition, within this survey, coals to be utilized in this program were identified.

Specific objectives were

1. To locate sources of processed smokeless fuel and to recommend those most suitable for use in the experimental emissions tests

2. To identify and select one or more natural smokeless fuels for test and comparison

3. To select one or more other solid fuels, of dissimilar characteristics to represent fuels not considered smokeless.

SCOPE AND LIMITATIONS OF COAL SELECTION

The selection of coals were limited to one type from each of the following classes:

- Processed smokeless fuel
- Anthracite
- Low volatile bituminous coal
- High volatile caking bituminous coal
- Western noncaking bituminous coal.

Practical considerations dictated the following limitations. The geographical source of each fuel should represent a substantial availability for domestic and commercial use of the type represented. Shipping distance and shipping facilities should be chosen to minimize cost of transporting the test fuel to Battelle. All fuels should be obtained in a size range appropriate for stokers, avoiding if possible the requirements for preparing a test fuel by hand methods at Battelle. The processed smokeless fuel should be obtained from a commercially operated process. These limitations were accommodated in the final selection of test fuels, as reported in detail later.

TECHNOLOGY OF PROCESSED SMOKELESS FUELS

SMOKELESS COMBUSTION

Smoke is a suspension of small solid particles in flue gases discharged during the burning of fuel. The particles are of two types--unburned residues of carbon formed by decomposed volatile material from the fuel, and ash remaining after the fuel is burned.

Any fuel may be burned smokelessly at suitable temperatures with enough oxygen, good mixing, and sufficient time to complete the combustion. It is important to burn the volatile matter completely before the temperature rises too high, because the carbon smoke particles formed by decomposition without oxygen are difficult to burn, and usually are lost as smoke.

A high volatile coal can give off as much as 40 percent of its weight as combustible vapors and gases when it is heated. These volatile gases burn rapidly compared to the carbon and require both a high rate of air supply and turbulent mixing to permit complete combustion. Even with sufficient air and complete mixing, conditions can exist in which the temperature is too low to ignite the entire combustible mixture. For example, the coal may be added to a cool fuel bed where there is no hot spot to ignite the tars and gases as they slowly distill. In another, the vapors and air may be adequately mixed at a sufficient temperature, but they may pass out of the combustion volume and be quenched by the cool surfaces in the boiler and flue. Any of these deficiencies result in carbon particles and condensed tar droplets that appear as smoke.

Coals with a volatile content of up to 25 percent by weight will burn smokelessly on beds when a few precautions are taken to provide the necessary temperature, turbulence, and time in the combustion zone. This tendency for smokeless combustion follows from the requirements for less combustion air to burn the volatiles, allowing more air to be available to burn the solid carbon in the fuel bed (which produces a hotter bed). Also, less mixing and time are required for complete combustion in the gas phase above the solid fuel bed than in the fuel bed.

NATURAL SMOKELESS FUELS

Natural smokeless fuels are found in all ranges of volatility. Anthracite with volatile content of only 2 to 10 percent burns smokelessly, but must be burned in combustion equipment designed for fuels with low volatile content. Low volatile smokeless fuels are commonly considered to be in the range of 12 to 22 percent volatile matter; these fuels can be burned with almost no smoke in conventional stokers. Moderate precautions must be taken for fuels with volatile contents in the range of 23 to 25 percent to achieve smokeless burning. (Processed smokeless fuels are usually supplied with about 8 to 15 percent volatile matter.)

The Pocahontas Seam of low volatile bituminous provides the true Pocahontas smokeless coal with about 18 percent volatile matter and also a "semi" Pocahontas from the same seam that has about 23 percent volatile matter.

PROCESSED SMOKELESS FUELS

Processed smokeless fuels were first prepared and marketed primarily as a convenience fuel for domestic use on open grates and in space heaters. The cost of processing was partially covered in some processes by briquetting fine coal that could not otherwise be used profitably. The convenience with which the processed fuel could be stored and burned always justified some price difference above natural fuels, but

this price differential in turn limited market growth until antipollution laws in the 1950's required their use of smokeless fuel. The largest markets for processed smokeless fuels developed in England and France, although many processes were studied in other countries without reaching commercialization.

Europeans developed a variety of smokeless fuels to satisfy the demands and preferences of consumers who used mostly hand-fired devices for comfort heating. These devices were relatively simple, because the Europeans conservatively minimized equipment cost by using open fireplaces and space heaters in their homes and establishments. The British retained a strong desire for an open flame as an aesthetic part of the heating device; this dictated the continued use of the open grate with only slight changes. In general, the open grate could not be designed to burn coal smokelessly except as processed smokeless fuels. Regional fuel restrictions required that only smokeless fuels be used in densely populated areas, so that captive markets developed.

Space heaters with glass panels in the front doors were later developed to permit a view of burning fuel. These were favorably received because they operate more efficiently and have a better natural draft to burn fuels of lower reactivity than are suitable for an open grate. These space heaters will not necessarily operate smokelessly, except with processed fuels. The requirements for smokeless fuels in the metropolitan regions remain in effect.

The United States did not develop corresponding increased markets for processed smokeless fuels for two reasons. First, natural gas became progressively available as pipelines were extended. It was sold at lower cost than solid fuel. Gas-burning equipment also reached the ultimate of automatic convenience that demanded no attention by the householder. Second, such development as occurred briefly in smokeless solid fuel uses, before natural gas was available everywhere, reflected basic differences between fuel markets in the United States and Europe.

Although many hand-fired coal units remained in service into the 1950's, Americans required central heating with automatic operation. Automatic coal firing was accomplished by a variety of stokers firing into warm air furnaces or boilers. Stokers were available and that could be adjusted to fire most of the regional coals efficiently and with minimum smoke. Thus, with the lack of stringent smoke ordinances, there was no need to develop a variety of smokeless fuels, since the appliances automatically maintained a fire in the furnace with occasional attention to refill the coal hopper. As a result, only two processes for smokeless fuels reached commercial production in the U.S. because of special situations. Their characteristic features provide a useful guide to smokeless fuel potentials in the United States today, as discussed in a following section.

CHARACTERISTICS DESIRED IN SMOKELESS FUELS

The characteristics of the various smokeless fuels, plus their significance in hand firing and in possible use in stokers in the United States are background for descriptions in subsequent sections of the processes used for manufacturing smokeless fuels.

Volatile Matter

The volatile matter in processed smokeless fuels is commonly about 15 percent which is in the range where smoke is not likely to be formed under almost any fuel-bed combustion condition. This amount of volatile is sufficient to permit easy ignition and maintenance of a stable fire in hand-fired units.

Ash

The ash content has secondary effects in the burning of smokeless fuel. An ash with low-fusion temperature may form clinkers in the fuel bed. Such clinkers cause poor air distribution through the grates and are difficult to discharge even if the grates are properly designed. High ash fusion temperature gives a powdery ash that can be allowed to build up in a layer to protect the grates from the hottest parts of the fire, and can be discharged easily by periodic shaking. However, almost any type of ash can be accommodated by skillful firing and/or equipment design. In coal regions with low ash fusion temperature, stokers were commonly designed to cause fusing of the ash into a ring at the bottom of the retort. The ring was removed once or twice daily in several large pieces with hand tongs. This was done at the same time the stoker hopper was refilled, and was regarded as not particularly difficult for the unskilled operator.

The amount of ash in any fuel depends upon ash content of the original coal, and the process used in pretreating it for smokeless operation. High ash content is a disadvantage to the consumer because of the larger amount of ash that must be dispersed.

Moisture

Processed smokeless fuels usually contain only small amounts of moisture when originally prepared because most processes require heating to remove a part of the natural volatile matter. Also, natural smokeless coals normally have only moderate amounts of moisture. Smokeless fuels prepared by briquetting of fines may contain large amounts of moisture after exposure to wet weather, if the binder used in briquetting does not impact water resistance to the product. This does not impair smokeless combustion of the fuel but is a disadvantage to the consumer because the fuel is purchased by weight.

Size

The size for domestic stokers is usually a double-screened fuel about 1-1/4 x 5/8 in. (32 x 16 mm). Top size is determined by the clearance

in the feed screw which is not much more than 1 inch. Some undersized fines are unavoidably formed during crushing, screening, and shipping. An undersize content of not over 15 percent is acceptable and may be beneficial in uniform feeding by the screw. An excess amount of fines may interfere with fuel bed air distribution.

The burning characteristics of anthracite differs from bituminous coal or processed smokeless fuel, and requires a different design of stoker with a wider, more shallow fuel bed. The size specified is about 9/16 x 5/16 in. (14 x 8 mm) for proper combustion in this type of bed.

Hand-fired smokeless fuels used in Great Britain are usually somewhat larger in top size, about 1-5/8 x 3/4 in. (40 x 19 mm), to give a more open fuel bed for better air flow without forced draft. Briquettes prepared as a smokeless fuel are usually about 1-1/2 to 2 in. (38 x 50 mm) in the largest dimension, either egg-shaped or pillow-shaped. Similar briquettes of processed smokeless fuel were obtained in the United States for these stoker tests; they are crushed and screened to stoker size.

Bulk Density

Processed smokeless fuels prepared by heating natural coal to drive off excess volatile matter contains many pores induced by swelling and release of the volatile matter, and their bulk density in size ranges for hand and stoker firing is usually about 440 kg/m^3 (26 lb/ft^3). Smokeless processed fuels that are prepared by briquetting fine sizes with a binder and then curing are about twice as dense. For the more dense fuels, a larger supply of fuel can be stored in the stoker hopper, or in the hand-fired fuel bed, thus requiring less frequent operator attention.

Strength

The strength of the processed smokeless fuel must be great enough to prevent excessive formation of fines during shipping and handling. Usually the low density chars from devolatilized coals tend to be somewhat friable, according to experience in England (14).

Adequate strength in a processed smokeless fuel may be more important in stoker firing than for hand firing, because the stoker screw applies more mechanical stress during the feeding of fuel from the hopper and pushing it into the retort. Mechanical strength of processed fuel can probably be adequately controlled by select process conditons. In addition, the coal must not be so hard and abrasive that the feeding of it causes excessive wear of the stoker screw.

Caking Properties and Swelling

Essentially all natural and processed smokeless fuels burn without excessive caking in the fuel bed (caking interferes with distribution of combustion air). Some of the strongly caking coals have been difficult to burn in domestic stokers because of formation of "coke trees" pushed up from the surface of the stoker retort. Although the strongly caking coals could be burned essentially without smoke, it may be necessary to break up the coke formations by manually probing the fuel bed.

Reactivity

Specifications for minimum reactivity of smokeless fuel have been directed towards minimizing attention and extending the attention interval in manually fired appliances. In particular, the ignitability of the fuel, and the recovery of an active fuel bed from a dormant fire have determined the preference for volatile matter in the processed fuel at levels exceeding 10 percent. The wide range of reactivity and ignitability permissible for stoker operation indicates that the development of smokeless fuels in the United States may be influenced more by process economics than by reactivity requirements.

SMOKELESS FUEL PROCESSES IN THE UNITED STATES

The Disco Process

In the 1930's and 40's, Disco low temperature coke was produced in a commercial plant by the Consolidation Coal Company to upgrade the fines recovered from a mine mouth coal-cleaning plant near Pittsburgh, Pennsylvania (B-2, B-3). The strongly caking Pittsburgh seam coal was modified by preoxidation of the fine feed with air at about 600 F (320 C) to reduce the plastic properties to a level that would form a sized product of carbonized balls by agglomeration in the Disco retort. This retort was an inclined rotating steel cylinder which was externally heated to maintain a temperature of about 1000 F (540 C) in the heating zone. As the fines followed a spiral path through the retort, mixing and cascading of the semiplastic charge resulted in agglomeration of individual particles into ball shapes that ranged from 1 to 6 in. (25 x 150 mm) in diameter. Commonly, size could be controlled more closely to a range of 1-1/2 to 3 or 4 inches (38 to 75 or 100 mm). At the exit of the retort the agglomerated product was screened from the residual fine low temperature char, cooled, and marketed as a premium fuel for residential heating. Fines were recycled by blending with feed to the retort.

The plant was closed in the late 40's, presumably because it was no longer profitable. Residential markets were declining, and cleaning plant fines could be used to prepare pulverized coal which was in demand for firing industrial and utility-steam boilers.

Low-Temperature Lignite Carbonization Process

A carbonization plant has been operating in Dickinson, North Dakota since 1928 to prepare a low-temperature smokeless lignite char. Lignite from the local strip mine is crushed and processed in two Lurgi carbonizers of conventional design (17). The crushed lignite is fed into a drying section, which is the topmost of three vertically superimposed sections of the carbonizer shaft. Drying gas circulates through the drying section, countercurrent to the slowly downward moving lignite. Standpipes at the bottom discharge the dried material into the middle carbonizing section. The drying gas maintains the drying section at about 500 F (260 C).

The carbonizing section is where a portion of the volatile matter is driven off. It operates at about 1100 F (590 C). These gases and volatile products are fed to a by-product treatment auxiliary system. Some by-product gas from the carbonization is burned in a combustor; the hot combustion products (at about 1100 F) (590 C) are used to heat the carbonizing section. The carbonized lignite is discharged through reciprocating grates at the bottom of the carbonization section. The grates control the downward flow of fuel through both drier and carbonizer. The grates discharge the fuel into the cooling section where the product is cooled by circulating cool gas and then discharged to a conveyor or pit for removal to storage. The fine char is ground and briquetted for sale.

This commercial operation has changed products as the markets demanded. Initially, the briquettes were prepared with a pitch binder derived from the process, and were cured by moderate heating and partial oxidation to give a hard long-burning smokeless fuel approximately equivalent to anthracite. Domestic heating by solid fuels continued in this area longer than in other parts of the country, because of the distance from the producing natural gas fields and the relatively small market offered by the scattered towns and small population. Coincident with the decline in the domestic market, the popularity of outdoor cooking and camping increased, so that there was a growing demand for briquettes suitably modified for grills and fireplaces. Recently, the shortages of oil and natural gas have suggested a potential market for fuel briquettes for space heaters. Lignite char briquettes are distributed widely as a replacement for wood charcoal and charcoal briquettes that are in short supply.

The modified briquettes are prepared with different binders and slightly different formulation, depending on the end use. Starch or corn flour binder has replaced pitch, because the flour is smokeless after drying at a lower temperature than is necessary for pitch binder. Domestic fuel briquettes made by this procedure are hard and burn reasonably long, but not quite so long as the pitch-bound briquettes. The formulation for outdoor grills and barbecues includes sawdust added to the char before briquetting, which gives a faster burning, hotter fire appropriate for cooking. The pitch-treating line is still used occasionally for making and curing batches of pitch briquettes to be sold on the local market. These use the substandard char obtained at the end of a continuous run with the Lurgi carbonizers as the carbonizers are being emptied.

TOSCOAL Process

The TOSCOAL process (18) has been operated in a 25-tpd pilot plant for retorting of Wyoming subbituminous coal to produce liquid and gas products, and a smokeless char. The raw coal feed is crushed to -3/4 in. (19 mm) and preheated by hot flue gas exhausted from a ceramic ball heater fired with process gas and air. The hot ceramic balls and preheated coal are introduced together into an inclined rotating pyrolysis drum where the coal is carbonized by the sensible heat of the balls. The drum discharges over a screen to separate the char for cooling and the warm balls for recycle to the ball heater.

About 80 percent of the heating value of the original coal is recovered in the char. The volatile matter varies with the temperature of the carbonizer, and is within the smokeless range of 15 to 25 percent.

The char has been tested as a pulverized boiler fuel. The Hardgrove grindability is acceptable for pulverizing. Thus, stoker-fuel briquettes could be manufactured from ground char. Since the process is set up to recover tar for liquid fuel use, it would probably be preferred to use a solid binder, such as corn flour, to prepare a solid stoker fuel.

COED Process

The COED process (19) has been studied in a pilot plant with a capacity of 36 metric tons of coal per day in which over 10,000 metric tons of coal have been treated. It can handle an agglomerating coal without pretreatment. Several fluidized beds in series devolatilize the coal without agglomeration and collect oil and gas as primary products. The beds successively dry the crushed coal and then devolatilize it at several increasing temperature levels just below the agglomeration temperature (which increases as volatile is removed) to produce a char. In the final bed, part of the char reacts with oxygen and steam to make a hot fluidizing gas that fluidizes and supplies carbonization heat to the other beds, and finally is discharged as the gas product. About 60 percent of the heating value of the raw feed is obtained as a 5 percent volatile char product from the devolatization steps. Part of the char stream might be diverted from the inlet of the final gasifying bed, and should be a suitable smokeless fuel with a volatile content of 12 to 15 percent.

The small size of the fluidized particles would require that the smokeless char be ground and briquetted with a binder for domestic and commercial stoker use. This option has not been studied as a part of the pilot plant development work.

SMOKELESS FUEL PROCESSES IN ENGLAND

A survey of the quality and characteristics of smokeless fuels readily available to domestic consumers in England covered seven processed fuels and anthracite (14). The following summaries indicate brand names and properties of these fuels.

Process Features and Fuel Characteristics

Anthracite--

This natural smokeless fuel is double screened to provide size ranges suitable for hand firing. There are four grades of anthracite marketed, representing two ranges of volatile content, above and below 6.5 percent, and two ranges of ash content, above and below 3 percent ash.

Phurnacite--

This is made by briquetting fine sizes of low volatile fuels. It is similar to natural anthracite: low volatile content, high density, igniting with difficulty in a hand-fired appliance. Briquettes of this

type are prepared from fine sizes of fuel from many sources and are widely available.

Presumably, similar briquettes could be made from the low volatile char produced in the final combustion stage of the COED process. These could be used in domestic stokers, because difficulty with ignition would not be a problem in automatic equipment.

Gas Coke or GLOCO--

Gas coke is a residue from the manufacture of coal gas for city distribution in England. GLOCO is a brand name for gas coke. There is no equivalent product in the United States, because coal gas as a domestic fuel has been entirely replaced by natural gas. Gas coke is a porous, low-density fuel (340 kg/m^3, 21 lb/ft^3) of nominal sizes 2 x 1 or 1-1/4 x 1/2 inch (50 x 25 or 32 x 12 mm). Because it is friable, there is likely to be considerable undersize material produced in shipping and handling.

SUNBRITE--

This trade name of the National Coal Board of Great Britain is applied to small sizes recovered from any hard coke plant. There is no official specification of properties. Two sizes for domestic use are nominally 1-1/2 x 1 inch (38 x 25 mm) and 1 inch x 1/2 inch (25 x 12 mm).

Hard coke of similar properties is recovered from coke ovens in the United States. Low volatility makes it a difficult fuel to hand fire in a domestic appliance in England, and the physical properties of high strength and abrasiveness would make it generally unsuitable for domestic stoker firing in the United States.

REXCO, COALITE, or WARMCO--These are low temperature cokes with similar properties. REXCO and COALITE are the products of private manufacturers, and WARMCO is marketed by the National Coal Board. Properties of the products reflect the quality and type of coal processed and the temperature of carbonization. REXCO is made in a number of different plants of the National Carbonizing Company throughout Egland. This brand of low-temperature coke was reported by the company to have a volatile content of about 7.6 percent. The fuel appeared to be fragile, with undersize excessive in many samples. Ignition performance was reportedly not good for any of these brands for manually tended open fires. The ignition would not be a problem in stoker firing, but undersize and friability presumably would make satisfactory control of a stoker fire difficult. Briquettes of the proper size for stoker firing, with smokeless binder properly cured after briquetting, would be acceptable in small automatic stokers.

PROCESS AND EQUIPMENT FOR REXCO SMOKELESS FUEL

The low temperature carbonization retort that produces REXCO fuel has undergone a long series of developments and improvements since the 1930's, and is discussed here as typical of a process that might be used in the United States to satisfy demands for processed smokeless fuel. All low

temperature coke processes use internal heating by recirculating the combustion products from fuel gas evolved during the carbonization (20). The original retorts were 10 feet (3.05 mm) in diameter and the process was intermittent, with repeated cycles of charging, carbonizing, and discharging the carbonized product. When the Clean Air Act was passed in England in 1956, demand increased and improved retorts were built along the same basic design as the original ones. The earlier improvements retained intermittent operations of the retort, but the refractory lining was reduced in thickness to increase capacity, and methods of handling the dondensate from the off gas were refined to reduce atmospheric pollution. All the burnable gas produced is used in the process, for carbonizing and for heat in the by-product refining steps.

The most recent improvement was an entirely new plant with continuous retorts, incorporating materials handling equipment, centralized automatic controls, auxiliary systems for recovering condensed tars and aqueous liquors as by-products, gas burners for heating the charge, product fuel quenching, classification, and bunker storage (21).

The REXCO plant is at the mine mouth of the Snibston Colliery, which supplies coal directly by conveyor from the coal washing plant. There are five identical continuous retorts, each with its own complete combustion system and gas treatment, plus hydraulically operated control units. The capacity of each retort is 200 metric tons of coal per day or 1000 metric tons per day total for the plant. Yield is about 75 percent so that the annual production of smokeless REXCO fuel by low temperature carbonization at this plant is more than 250,000 metric tons per year. The plant was operating at full capacity in 1974. The National Carbonizing Company has three older plants also operating, so that the total capacity for REXCO fuel of all grades is about 900,000 metric tons per year (22). It also has been reported that the REXCO continuous process would be used to carbonize raw briquettes to produce smokeless Phurnacite (23).

SELECTED FEATURES OF OTHER SMOKELESS FUEL PROCESSES

Fluidized-Bed Low-Temperature Carbonization

Fluidized beds for partial devolatilization of coal fines to produce a low-temperature coke have advantages characteristic of all fluidized beds in that (1) a uniform temperature is maintained and controlled throughout the bed volume, (2) rapid heat transfer is attained between fluidizing gas and solid particles for either heating or cooling, and (3) that the solids are easily handled into and out of the bed because they will flow like a liquid when properly fluidized. Continuous withdrawal of the product at carbonization temperature is several pilot-plant tests has permitted briquetting of the hot char while it is still semiplastic without the necessity for using an added binder or for reheating in the briquetting process.

Substantial pilot-plant operations and commercial-scale experimental runs were carried out in the 1960's.

No substantial commercial production of smokeless fuels in fluidized-bed carbonizers is known at the present time. Presumably the advantages of fluidized beds cited above are counterbalanced by the known disadvantages of excessive carryover that may be induced by size degradation of a friable solid, such as low-temperature coke, during fluidization.

Methods for Curing Briquettes

Briquettes with a pitch binder should be cured to insure smokeless combustion in hand firing, and to improve the mechanical properties of strength, water resistance, and resistance to temperature shock and crumbling in the fuel bed.

Mild heat treatment in the presence of a gas containing several percent oxygen at a temperature of about 660 F (350 C) produces a stable briquette by oxidation of the briquette surface and polymerization of the pitch binder with substantial increase in its softening temperature. Commercial processes in the Netherlands and France have used a number of variations. Some plants have multiple intermittently charged curing reactors for treating briquettes for about an hour with flue gases containing about 50 percent air. A continuous curing process employed a traveling grate with the oxygenated flue gas forced upward through the bars.

In the preceding section it was noted that a modified REXCO continuous carbonizer was scheduled for operation in curing briquettes under similar conditions.

A fludized-bed briquette-curing process developed in France by the National Institute of the Carbonization Industry (INICHAR) (B24) uses a fludized bed of sand particles in which the green briquettes are immersed while the treatment mixture flows continuously from the inlet to the exit of a fludizing trough. The sand is preheated to about 400 C and the cold briquettes are added to the fluidized briquette preheating zone where they are raised to a temperature of over 300 C before they flow continuously over a weir with some sand into the curing zone. In the curing zone they pass over multiple hot gas inlets that maintain fluidization of the sand-briquette mixture. Because of reaction with the oxygen in the fluidizing gas the temperature slowly rises until they are discharged at about 360 C over the exit weir. They travel over an inclined screen that separates and recycles the sand and fines before the cured briquettes are discharged onto a cooling conveyor to storage.

Because it is probable that stoker-sized smokeless processed fuel must be agglomerated or pelletized by some method, these various procedures for curing briquettes are of interest when considering the potential use of smokeless processed fuel for stokers. The pellets (small briquettes) must be cured in some manner to provide adequate mechanical resistance to degradation in the stoker screw and sufficient heat resistance so that they

do not spall or disintegrate in the stoker fuel bed. Lack of heat resistance has been a problem in many pelletizing and briquetting operations that use smokeless binders, such as those used in the lignite-char briquettes described in the section on United States processes.

SOURCES OF TEST FUELS

The guidelines for selecting specific sources of the five typical fuels for the test program were described early under Scope and Limitations. This section presents a description of the fuels selected and procured for stoker emission tests. The basis for selection and some of the alternatives considered are described.

Processed Smokeless Fuel

Lignite char briquettes were purchased from Husky Industries of Dickenson, North Dakota. This was the only acceptable U.S. source of processed smokeless fuel from a commercial process.

Other sources considered were from the pilot plant processes described previously. TOSCOAL was not available in sufficient quantity for the test, and would have had to be obtained by a custom run of the pilot plant for one day with production of at least 25 tons of char from Western coal. This char would have had to been pelletized or briquetted in another custom operation. No effort was made to locate a source for briquetting.

COED char was not available because the pilot plant is not now in operation, awaiting the possibility of the renewal of the government operating contract. Even if obtainable, the processed COED char would also have had to be briquetted in a custom operation.

The possibility was considered of using briquettes from an intermediate stage of the manufacture of formed coke by a proprietary process of the FMC Corporation. The briquets are made from a Western coal char that is ground after low temperature carbonization, briquetted with a proprietary binder, cured, and then carbonized to a low volatile content for metallurgical use. It seemed possible that the cured briquettes would have volatile content in the preferred range before the carbonization step. We were advised that they should not be used, as they were not typical or suitable for a domestic stoker fuel.

Importing a processed smokeless fuel from England was ruled out on several considerations. The cost including packaging and shipment to Battelle-Columbus was prohibitive at an estimated $700 per metric ton. The product was not necessarily typical of any processed fuel made from American coal. None of the processed fuels in England are intended for stoker firing and probably would not be suitable.

Anthracite

There were no retail sources for anthracite in the Columbus area. Accordingly, an experimental lot of Number 1 Buckwheat Pennsylvania anthracite in 50 pound bags was obtained from the mine operated by Beltrami Enterprises, Inc., through the GA Fuel Sales, Division of Blue Coal Corporation, P.O. Box 568, Wilkes-Barre, Pennsylvania 19703.

Low Volatile Bituminous Coal

A search for sources of low volatile bituminous coal determined that most of the low volatile from the Pocahontas seam is preempted for blending with other coals to make metallurgical coke. It is shipped to the coke ovens as mine run sizes. Through the assistance of many persons in the Consolidation Coal Company, a shipment of low volatile bituminous coal (Pocahontas Number 3 seam) was procured from the Bishop mine at Bishop, Virginia.

High Volatile Caking Bituminous Coal

A stoker coal of this classification was available locally in the Columbus area and was marketed by the South East Coal Sales Company of Columbus. The coal procured was an Eastern Kentucky coal mined by the Southeast Coal Company, Irvine, Kentucky, at their Polly mine from the Upper Elkhorn Number 3 seam. The Elkhorn Number 3 seam is a high volatile B bituminous coal.

Western Noncaking Bituminous Coal

Several mines listed in the 1973 Keystone Coal Industry Manual (25) as producers of stoker size Western coal were selected for consideration. Alternate coals from Kansas and Wyoming were also considered. The Kansas coal appeared unsuitable because it was from the Western Region of the Interior Province, and was not regarded as a typical Western coal.

A Wyoming coal from the Elkol mine of the Kemmerrer Coal Company in Lincoln County, Wyoming, was considered. This is a subbituminous B coal from an Adaville seam, of which there are several. The composite analysis of the adaville seams is - moisture, 21 percent; ash, 3.6 percent; sulfur, 0.6 percent; heating value, 9700 Btu per pound. This coal is lower rank with higher moisture and presumably would be somewhat more reactive than the Colorado coal if it were made into a char and briquetted. However, the test lot of processed and briquetted lignite char is also an example of high moisture, low rank fuel of high reactivity and the Colorado coal appeared to be a better choice for achieving a range of characteristic properties among the five test lots.

The final selection was the Corley strip mine in Fremont County, Colorado, which prepares an air-cleaned stoker coal. This coal was mined from the Black Diamond seam.

ENVIRONMENTAL CONSIDERATIONS

The use in stokers of smokeless fuel prepared by low-temperature carbonization of coals from various areas requires consideration of environmental impacts of emissions from the manufacturing plant and from the stokers as well.

STOKER EMISSIONS FROM PROCESSED COAL

It is anticipated that particulate and POM emissions from firing a processed smokeless fuel in stokers would be less than those from firing a high volatile bituminous coal. This expected result is based upon the particulate and smoke emissions of stokers firing low volatile coal that are generally lower than high volatile coals. There are no data available as to the performance of a stoker firing this fuel.

One potential problem that will be considered from firing a processed smokeless fuel is the possible loss of ignition during the "holdfire" period. During seasonal changes, stokers often run only 5 minutes during a 30-minute cycle. With the low volatile content of the smokeless fuel, the raw coal fed into the retort may not ignite properly and burn uniformly because of the low-bed temperatures. It may be necessary to operate the stoker for longer than 5 minutes every cycle to maintain a suitable fuel bed to ignite the raw coal.

FUEL-PROCESSING PLANT EMISSIONS

All smokeless-fuel processing plants in the United States will be new. An appraisal of the overall significance of plant emissions from these sources must depend on estimates of prcesses to be used, size and location of individual plants, and the rate at which they are constructed to satisfy market demands. A projection of the qualitative course of such developments is presented in the next section, but formal environmental impact assessments with quantitative treatment of individual plant emissions is not justified here, in the absence of a more definitive data base.

As a useful alternative, the literature study of processing methods provided background information for a qualitative summary of pollution sources from a processing plant. Process operations identified in the literature study indicate that the pollution potential and the emission of pollutants is similar to those from an oven (metallurgical) coke plant. The older designs of coke plants used intermittent charging of coal and intermittent discharge by pushing the hot coke into an open-top receiver and quenching with water. By-product coke ovens condensed the volatile matter given off during coking as tar and aqueous ammoniacal liquor. Uncondensed gas was scrubbed and purified before use as fuel in the process or for sale. Much of the pollution from coke ovens was from pushing and quenching the coke in

open air, and from the release of particulates when a coal charge was dumped into the oven.

Conventional low-temperature carbonization processes similarly operate intermittently. They differ from coke ovens in heating the charge internally by the combustion products from process gas, instead of through the oven walls as in coke oven. Light oils are produced in greater quantities than the high temperature tar. The more volatile oils require somewhat more efficient gas-scrubbing apparatus for equivalent purification of the gas. There is no important difference in pollution potential, because the gas for process heat is burned to nonpolluting combustion products in the heating furnaces of both processes.

Considerable recent information is available in the engineering literature on the improvement of coke into closed containers for quenching. This literature was not covered as part of the smokeless fuel survey, but would be available for detailed background information if it were necessary to prepare a formal environmental impact assessment for a planned low temperature carbonization plant. Operational details would also be available from the low temperature carbonization plant at the Snibston Colliery in England (B-5), if a specific site for a United States plant were being considered.

For the qualitative requirements of this survey, it is useful to list the following features at Snibston that are claimed to virtually eliminate pollution sources.

- The plant is located on 40 acres adjacent to a mine which normally supplies all requirements for raw coal feed. Transportation with loading and unloading of coal by conventional means is eliminated. A conveyor supplies coal directly from the mine preparation plant to a storage bunker.

- The storage bunkers are filled separately with various sizes of coal from the mine screening plants and blends for use in the process are automatically delivered to a continuous conveyor.

- The blend is passed through a final screening to remove fines and then proceeds by conveyor to each of the five continuous retorts.

- Each retort operates independently with its own gas scrubbers, combustion chambers, condensers and hydraulic units, so that a shutdown or beginning of a campaign does not overload or disrupt the operation of the other independent systems, with accompanying possibility of overflows or bypassing of materials in process.

- Each retort discharges its smokeless fuel into a water seal, which quenches the charge and is the underwater inlet for a drag conveyor feeding the storage bunkers. This method of discharge and disposal minimizes dust and odor from the quenching and handling process.

- A waste gas incinerator burns or decomposes traces of pollutants in the aqueous liquor and the waste gas so that noxious materials are burned before discharge.

- The central control panel at the plant registers and controls the coal feed, conveyor handling, and the operation of the retorts. Thus, the probability of malfunctions is reduced, and precise control insures that operations are maintained for minimum pollution as well as maximum production.

An additional operation that has pollution potential is the curing of briquettes. It has been noted above (20) that the REXCO continuous retort also was planned for use to carbonize smokeless briquettes, with equal potential for reducing possible emissions from the briquette carbonizing process.

The fluidized hot-sand cure for briquettes (21) was reported to be an efficient procedure because of improved temperature and time control during processing, and no weight change. The cure should produce little pollution from the effluents. The volatile loss is less than 2 percent during the curing operation because of the precise temperature control. Low temperature oxidation hardens the briquette surface, with retention of about 2 percent by weight of oxygen to balance the small volatile loss.

EVALUATION AND INTERPRETATION OF THE SMOKELESS COAL SURVEY

ANALYSIS OF SMOKELESS COAL

Smokeless coal is defined as having less than 25 percent volatile matter. It is believed that many higher volatile coals can be burned smokelessly in a properly designed and adjusted stoker. This conclusion was verified in experimental studies for the Eastern and Western high volatile coal.

SUITABILITY

The suitable process for manufacturing smokeless coal is one that uses low-temperature carbonization of the high volatile raw coal followed by further processing to produce a fuel of acceptable characteristics for feeding and combustion in a stoker. These characteristics include adequate mechanical strength, thermal resistance to spalling in the stoker fuel bed,

and low abrasiveness within the capabilities of the stoker screw to handle without excessive wear. The process probably must include a briquetting or pelletizing step with curing of the briquettes (pellets) for adequate strength.

Oven coke breeze could be burned in a stoker but would be too abrasive. Low-temperature char is probably too friable for use in a stoker.

ENVIRONMENTAL IMPACT

Stokers can be adjusted to burn solid fuels smokelessly. All of the organic sulfur and much of the pyritic sulfur in the coal will appear as sulfur dioxide in the flue gases from the stoker-fired furnace. POM emissions will also be present. Although these are tarry materials, concentrations of possible environmental interest may not be visible nor detectable by odor. Sensitive techniques can be used to identify POM emissions but the quantitative significance of their environmental impact at the detectable concentrations has not yet been defined.

The environmental impact of individual smokeless coal process plants can be controlled by applying known antipollution principles to the design of new plants. There is only one smokeless fuel plant operating on a commercial scale in the United States. It is in full production to supply domestic hand-fired markets so that new stoker markets will have to be supplied predominantly by newly designed plants with the necessary antipollution safeguards.

LONG- AND SHORT-TERM AVAILABILITY

There is no production of processed smokeless coal for stoker use at the present time. Short-term availability must depend upon natural smokeless fuels. Low-volatile smokeless bituminous coals are in short supply for metallurgical uses. The supply of anthracite would be adequate to supply anthracite burning stokers. This supply could be expanded with reasonable speed as fast as anthracite stokers could be manufactured and installed for its use. If high volatile coal can be included in the smokeless category when burned in modified stokers, then short-term availability is subject only to the general problems of supplying coal to meet increasing demands of the total market. If a smokeless coal is also defined as one with suitably low sulfur emissions, the problems of short-term availability will be the same as for any other use that limits sulfur content in the effluent.

The long-term availability of smokeless coal depends on the growth of a profitable market. If processed smokeless fuel must be manufactured, processing plants must first be built. Their availability will depend on advanced planning with possible subsidies or favorable profit prospects in the economics of processing coal to produce a product with an acceptable smokeless composition.

ECONOMICS

The economics of smokeless solid fuel production and marketing depends on the following influences which are not well defined. The unit cost of the heat energy developed from a processed smokeless coal by burning it in a stoker will be higher than unprocessed coal, because the process is less than 100 percent efficient, and the capital and operating costs must be covered as well. Past experience with low-temperature carbonization has shown that by-product credits were no higher than the equivalent fuel value of the recovered tar. A review of the possibility that by-product credits may be increased by the current shortage of liquid petroleum products is beyond the scope of this study.

A subjective judgment derived from this smokeless fuel survey is that the economics of smokeless fuel processes may be unfavorable if compared with development of improved designs of domestic and commercial stokers that are adjustable to burn various regional coals really smokelessly. Devolatilization processes to produce conventional smokeless fuels are not specifically directed toward the use of such fuels in a stoker. Adapting these fuels for stoker use by briquetting introduces an added economic penalty.

If sulfur emissions must also be controlled, then the use of a low-sulfur coal or a process that removes a substantial part of the sulfur in high-sulfur coals might be required. (Small stokers cannot be designed at reasonable cost or adjusted to eliminate sulfur in the flue gas.) The economics of eliminating POM from stoker emissions is unknown until the extent and character of such emissions is measured.

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